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1952

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This volume contains contributions from the

WOODS HOLE OCEANOGRAPHIC INSTITUTION

which appeared in 1952 in publications other than

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for the year 1952

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Contribution No. 537

2.4. STREAKS OF NATURAL WATER SURFACES

H. STOMMEL

*Woods Hole Oceanographic Institution**
Woods Hole, Mass.

International Symposium on Atmospheric Turbulence in the Boundary Layer
4 – 8 June, 1951
GEOPHYSICAL RESEARCH PAPERS NO. 19

ABSTRACT

Different types of natural streaks are described. Results of a year's observations at a single pond are tabulated. Various theories of streaks are discussed, and a new streak forming mechanism is introduced.

Massachusetts Institute of Technology, Geophysics Research Directorate
AIR FORCE CAMBRIDGE RESEARCH CENTER
Cambridge, Massachusetts
December, 1952

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* Contribution No. 537.

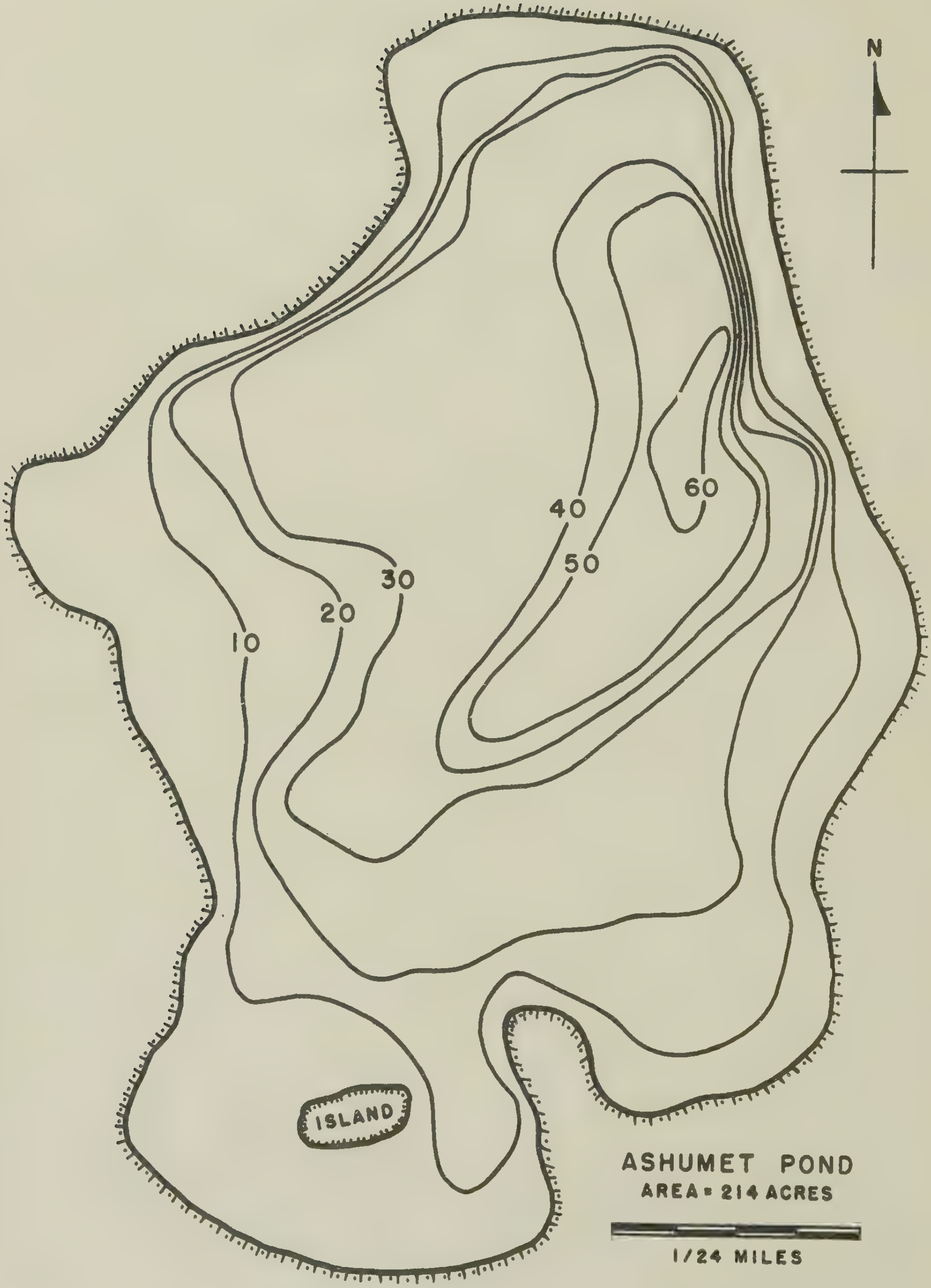
N
10
20
30
40
50
60
ISLAND
ASHUMET POND
AREA = 214 ACRES
1/24 MILES

Fig. 2.4.1. Physical details of Ashumet Pond on Cape Cod where observations were made.

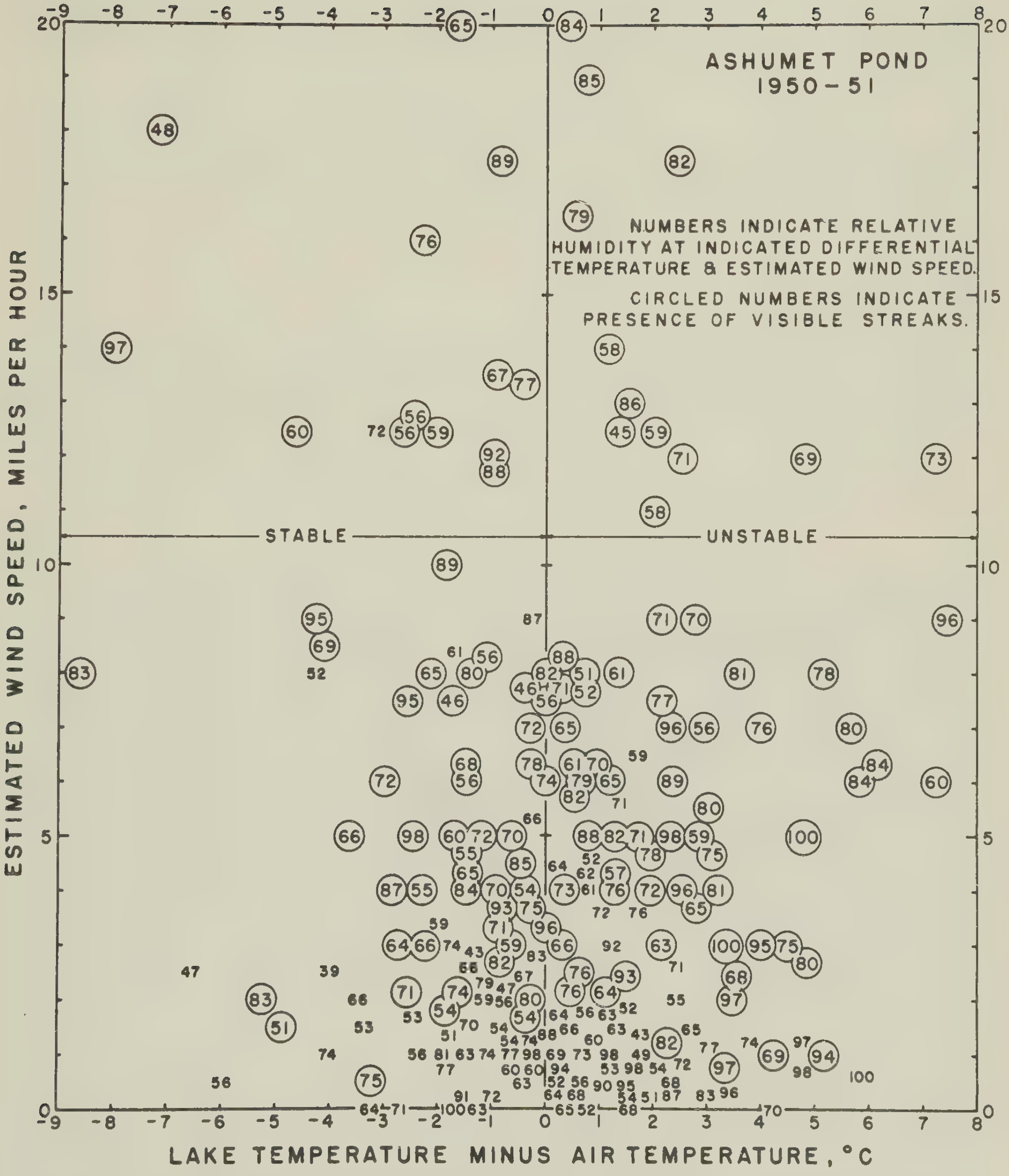

Fig. 2.4.2. Streaks in relation to atmospheric stability, wind speed, and relative humidity of air just above the pond.

2.4.1. INTRODUCTION

Most natural bodies of water exhibit a streaky appearance under the influence of the wind. The streaks consist of accumulations of floating objects such as foam, leaves, or films of oil. The process which causes these streaks has been a matter of considerable speculation and investigation; the following theories have been proposed: (i) air-cell theory — that there is a regular pattern in the wind over the water analogous to Rayleigh convection cells which sweeps objects on the water surface into linear arrays; (ii) wind-induced water-cell theory (Langmuir) — that a cellular motion of the top layer of water is induced directly by the wind, the nature of this process being in some way involved in the formation of the thermocline but unexplained, and that the streaks are regions of surface convergence; (iii) the convection-cell theory (Woodcock) — that a cellular motion of the water is maintained by convective overturning.

2.4.2. EXPERIMENTAL PROGRAM AND RESULTS

The observations of streaks upon which most ideas concerning their causes have been based have for the most part been at selected times and seasons so that it seemed desirable to collect observations at a single place during the course of a year. Because a limnophysical research program was already being pursued on Ashumet Pond, a small fresh water lake on Cape Cod of roughly ½ mi diameter and average depth of 30 ft (Fig. 2.4.1), physical observations of streaks were made and were spaced throughout almost a whole year. In all cases, regardless of stability conditions (i.e. lake — air temperatures) or relative humidity of air just above the pond, there were streaks whenever the wind was greater than 10 knots as shown in Fig. 2.4.2. For winds less than 10 knots, occasionally there were streaks present and occasionally not, but apparently their occurrence or non-occurrence was not dependent upon either the stability or relative humidity. The observational data are presented in Table 2.4.1. Experiments using ballasted bottles (such as those used by Woodcock) indicated a convergence of surface water into the streaks, but these convergent motions did not apparently extend as far down as the thermocline. Because traverses made with a thermocouple

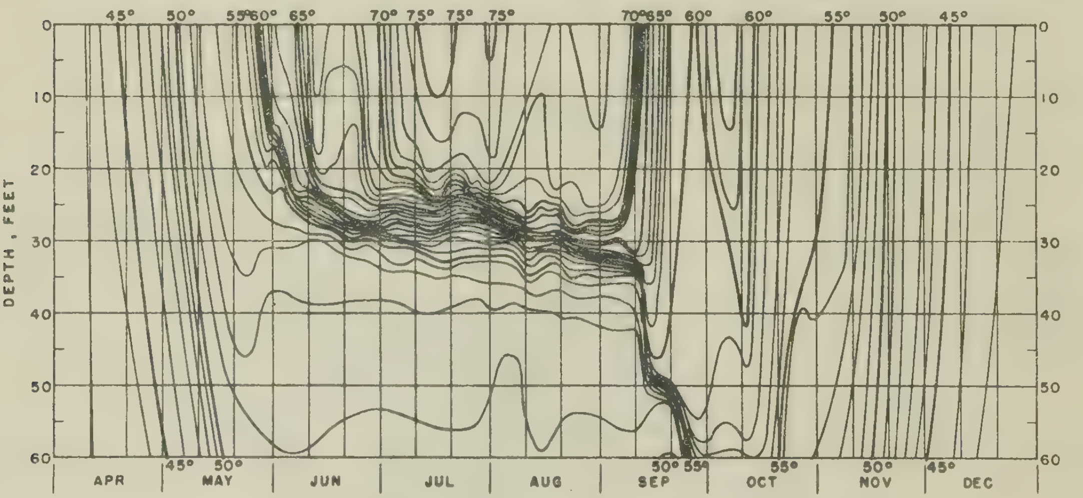

Fig. 2.4.3. Temperature profile of Ashumet Pond — 1950. Temperatures are in degrees Fahrenheit.

sensitive to 0.01°C did not reveal a correlation of the position of streaks and temperature fluctuations, and because the streaks appeared while the pond was warming up and cooling off, it seemed that they were not necessarily a thermal convective phenomenon. The temperature profile in the pond for 1950 is portrayed in Fig. 2.4.3.

2.4.3. FEATURES SHOWN BY MOTION PICTURE PHOTOGRAPHY

A number of motion pictures were made of the streaks on Ashumet Pond, and also some other ponds nearby on Cape Cod. When these pictures were shown at about 80 times their normal speed, certain interesting features of the streaks were visible which otherwise tend to escape the eye. First of all, the gusty and turbulent nature of the wind over the water immediately became obvious so that one can be sure that the streaks are not the result of any permanent structure in the wind itself. Secondly, under a steady wind the streaks have an amazing permanence and hold a mean position about which they waver, much like the way a flag waves in the wind without changing its mean position. If the wind changes its direction abruptly, the streaks themselves are quickly reoriented (in a matter of one or two minutes only). The speed with which this reorientation is achieved seems to the writer to suggest, as do so many other facts in his study of Ashumet Pond, that the mechanism which is responsible for the formation of the streaks is confined to a relatively shallow portion of the epilimnion.

2.4.4. A PROPOSED MECHANISM FOR THE FORMATION OF STREAKS

In casting about for a mechanism by which streaks on the surface can be produced other than the cellular theories that have been proposed, and which in the case of Ashumet Pond do not seem to explain all the observations, the writer has been led to consider the following type of mechanism. The striking thing about the surface tension within streaks is that it differs from that of the surrounding water. Ordinarily we would expect on calm water that an oil-film contamination would spread until it reached a monomolecular thickness, in which case the surface tension within the area of contamination would not be different from that outside of the area of contamination. A difference of surface tension within the two areas can be maintained only if the contaminated area is compressed in some manner, and it seems conceivable to the writer that although such a compression might result from surface convergence and sinking if there were active convection in the water, it could also happen if the small wind capillary waves which are produced in the area of clean surface and are damped out by the contaminated areas can exert a pressure on the contaminated areas. The pressure exerted by the small capillary waves would be greatest at the up-wind edge of the contaminated area, but would also tend to compress the contaminated area along its sides, due to diffraction of capillary ripples along the edges of the contaminated area. The capillary waves would exert a pressure depending upon their amplitude and wave length. However, they could compress the contaminated area only up to a certain point because the surface pressure in the contaminated area increases with compression. The amplitude and frequency of the capillary waves depend not only on wind speed but also on fetch and cross wind dimensions for the individual clear areas. This interaction of capillary wave pressure against the surface pressure of the contaminated area permits cross wind components of force to come into play and might therefore be capable of maintaining a very shallow helical cellular motion even against an adverse vertical density gradient.

Before advancing this notion with any degree of confidence it will be necessary to make some quantitative estimates of the magnitude of the forces involved.

Table 2.4.1. Visual observation of natural streaks of Ashumet Pond.

Month and Day 1950	Time EST	TEMPERATURES			Rel. humid. percent	Wind speed		Percent clouds	Streaks present
		Lake − air °C	Wet bulb °F	Dry bulb °F		Pond	Otis		
Apr. 18	1515	−7.2	48.8	58.8	48	—	18	80	Yes
May 1	1425	−3.1	50.4	55.2	72	10–15	8	100	No
3	1045	−1.8	43.8	53.0	46	5–10	10	20	Yes
5	1032	0.2	47.5	52.2	71	5–10	12	100	Yes
11	0945	−4.3	54.1	64.2	52	—	16	100	No
15	0955	+0.6	51.0	55.2	76	0–5	12	90	Yes
17	1315	2.4	48.3	51.1	82	15–20	16	40	Yes
18	0945	1.3	43.5	53.1	45	10–15	11	90	Yes
22	1230	2.1	48.6	52.2	77	5–10	7	0	Yes
28	0930	−1.1	60.0	64.1	79	0–5	4	70	No
June 1	1435	−0.9	63.6	65.8	89	15–20	16	100	Yes
2	1000	−2.4	58.5	68.3	56	0–2	6	0	No
	1245	−2.6	57.0	68.8	56	10–15	14	20	Yes
	1430	−2.5	57.0	68.8	56	10–15	14	60	Yes
5	0840	−0.2	52.2	63.4	46	5–10	6	20	Yes
	1030	−1.1	53.0	65.2	43	0–5	2	80	No
6	0845	−1.5	60.4	68.5	63	0–2	4	10	No
	1045	−1.7	60.2	68.7	61	5–10	8	10	No
	1245	−2.1	60.8	70.0	59	10–15	12	0	Yes
	1450	−1.7	60.5	68.0	65	20+	13	10	Yes
7	0845	−6.0	65.6	76.6	56	0–1	0	50	No
	1025	−6.6	65.0	79.1	47	0–5	0	70	No
	1245	−4.9	54.8	77.2	51	0–3	6	80	Yes
8	0845	−2.5	65.6	72.2	71	0–4	9	0	Yes
	1015	−3.7	66.6	74.5	66	5+	6	0	Yes
	1230	−4.7	67.0	76.8	60	10–15	15	30	Yes
9	1415	−2.1	64.2	72.1	65	8	15	40	Yes
12	0915	−4.0	49.8	62.5	39	2.5	6	0	No
13	0915	+2.9	54.3	63.2	56	7	10	100	Yes
	1315	+2.0	56.2	65.0	58	11	15	90	Yes
14	0820	+3.1	57.2	62.0	75	5	10	100	Yes
	1030	+2.5	57.8	63.4	72	0–2	5	90	No
	1730	+1.7	59.1	65.0	71	5	3	90+	Yes
15	0900	+0.4	60.0	67.2	66	1.5	5	80	No
	1330	+0.2	60.7	68.7	64	2	8	40	No
16	0900	−0.5	57.0	68.9	47	2	4	0	No
	1200	−0.4	60.2	70.6	54	4	6	5	Yes
19	0900	+2.6	55.0	61.7	65	1.5	4	100	No
20	0845	+0.7	60.2	65.8	73	1	0	20	No
	1345	+4.8	60.2	60.2	100	5	12	80	Yes
21	0830	+0.2	67.3	68.5	94	1.5	7	100	No
	1300	−1.5	68.1	71.6	84	4	11	80	Yes
22	0830	+1.9	52.3	64.4	43	1.2	9	80	No
	1015	—	54.1	67.2	42	0.5	3	80	No
	1250	+1.6	56.1	66.0	55	—	7	80	No
23	0835	+0.9	60.4	66.7	70	6	14	0	Yes
	1030	+0.3	60.4	68.0	65	7	15	0	Yes
	1236	−1.1	60.6	70.6	56	8	17	0	Yes
	1445	−1.5	61.4	71.6	56	6	11	0	Yes
26	0830	−1.5	65.0	72.9	65	4	13	10	Yes
	1030	+0.5	64.1	69.3	76	2.5	13	20	Yes
	1300	+2.2	63.1	66.8	82	1.0	8	30	Yes

Table 2.4.1. (Continued):

Month and Day 1950	Time EST	TEMPERATURES			Rel. humid. percent	Wind speed		Percent clouds	Streaks present
		Lake − air °C	Wet bulb °F	Dry bulb °F		Pond	Otis		
June 27	0915	+4.0	62.9	63.8	95	3	12	100	Yes
	1300	+2.6	65.0	65.8	96	4	10	100	Yes
28	0820	+2.1	59.1	66.0	71	9	10	0	Yes
29	0850	−0.3	63.6	71.3	66	5	8	80	No
	1110	−1.7	64.6	74.1	60	5	3	80	Yes
30	0900	+1.1	67.1	69.1	90	5	3	90+	No
	1045	−3.2	68.1	76.8	64	—	4	80	No
July 5	0830	−2.7	72.0	79.3	71	—	4	80	No
	1030	−1.0	70.0	76.8	72	—	10	90+	No
	1230	−1.5	71.1	78.3	70	2	8	80	No
7	0830	+2.8	62.9	69.4	70	9	10	90	Yes
	1030	+1.3	63.5	72.5	61	8	12	80	Yes
	1240	+1.2	64.6	72.7	65	6	14	90	Yes
8	0905	+0.4	66.6	74.0	68	—	3	90	No
	1230	−1.2	70.8	77.1	74	1	0	90	No
	1430	−0.5	67.4	76.3	63	1	5	80	No
11	1045	+3.4	70.1	70.9	96	0–1	5	100	No
	1050	+1.4	71.6	72.7	95	0–1	5	100	No
	1245	−0.2	73.2	76.0	88	1–2	6	90+	No
	1445	−0.9	73.4	77.6	82	3	9	80	Yes
13	0845	−0.3	71.4	76.0	80	2	6	40	Yes
	1030	−0.7	71.7	77.3	77	1	7	30	No
	1245	−1.3	72.0	78.8	72	5	9	30	Yes
14	0835	+1.1	62.1	71.7	58	14	3	90	Yes
18	0830	−1.9	73.8	78.2	81	1	8	0	No
	1010	−3.0	73.6	80.7	72	6	5	5	Yes
	1235	−2.3	73.8	79.6	76	16	15	30	Yes
19	0845	+1.3	62.5	72.8	57	4	12	80	Yes
	1230	−0.8	67.6	77.8	59	3	5	80	Yes
21	0845	+3.4	58.1	68.0	55	2	9	30	No
	1045	+2.1	60.1	70.6	54	1	5	30	No
	1300	+1.8	59.5	71.5	49	1	10	20	No
24	0845	+2.2	64.0	70.9	68	1	7	20	No
	1215	+2.3	64.4	71.0	71	3	4	40	Yes
	1420	+2.1	63.0	71.4	63	3	9	70	Yes
25	0835	+1.2	70.6	72.3	92	3	8	90+	No
	1230	+2.3	70.2	71.0	96	7	10	40	Yes
	1430	+2.2	71.0	71.4	98	5	19	10	Yes
27	0835	+2.4	64.0	70.4	71	3	6	0	No
	1140	−1.8	67.0	78.9	54	2	10	40	Yes
	1400	−0.4	65.5	76.9	54	2	15	60	Yes
28	0825	−0.4	66.2	75.9	60	1	0	20	No
	1030	0.0	68.0	75.5	69	1	7	30	No
	1235	−2.4	68.5	80.2	55	4	12	60	Yes
	1430	−1.6	66.9	78.4	55	5	13	40	Yes
31	0855	−1.4	70.4	79.0	66	2–3	5	30	No
	1044	−3.4	70.1	83.2	53	1–2	10	0	No
	1240	−3.0	69.6	82.4	53	—	14	5	Yes
Aug. 1	0845	+0.7	73.4	75.5	51	8	11	100	Yes
	1240	+0.7	73.6	75.5	52	8	12	100	Yes
2	0900	+5.1	65.5	66.0	97	3	10	100	No
	1315	+3.6	65.0	69.0	81	8	12	100	Yes

Table 2.4.1. (Continued):

Month and Day 1950	Time EST	TEMPERATURES			Rel. humid. percent	Wind speed		Percent clouds	Streaks present
		Lake − air °C	Wet bulb °F	Dry bulb °F		Pond	Otis		
Aug. 4	0820	+3.0	66.8	70.4	83	—	0	90+	No
	1042	+2.3	69.2	72.0	87	1	0	80	No
	1245	+0.1	68.0	76.4	66	3	6	70	Yes
7	0835	+5.6	60.3	64.1	80	7	13	80	Yes
	1045	+5.1	60.2	64.6	78	8	14	90+	Yes
	1430	+4.0	61.2	66.3	76	7	13	100	Yes
8	0830	+3.1	61.5	66.2	77	1	5	80	No
	1045	+0.9	61.6	70.6	60	1	4	70	No
	1400	−0.5	62.0	73.1	54	1	4	70	No
9	0830	−3.5	66.6	74.7	66	2	7	20	No
9	1045	−2.0	66.7	77.0	59	3	9	40	No
	1445	−1.5	67.9	75.4	68	6	15	70	Yes
10	0845	+1.4	68.0	69.6	93	2	15	100	Yes
	1245	−1.7	69.8	75.7	74	2	12	100	Yes
14	0840	+1.9	63.0	69.0	72	4	10	10	Yes
	1045	+0.7	61.3	71.5	56	2	8	30	No
	1255	−0.7	63.4	74.3	54	1	7	80	No
15	0830	−1.2	66.5	75.6	63	1	0	50	No
	1030	−1.7	64.5	76.8	51	2	9	30	No
	1300	−0.7	65.0	75.7	56	2	12	5	No
16	0815	−1.0	65.0	75.1	59	2	16	40	No
	1040	−0.2	67.9	73.7	75	4	12	30	Yes
	1310	−0.3	67.9	74.3	72	7	16	40	Yes
	1500	−0.7	68.1	75.0	70	5	14	20	Yes
17	0830	−0.9	68.5	75.2	71	3	10	80	Yes
	1035	−2.4	69.7	78.2	66	3	15	50	Yes
	1300	−2.7	70.0	79.0	64	3	16	60	Yes
18	0830	+0.6	68.0	72.7	79	6	11	90+	Yes
	1040	+0.0	69.9	74.0	82	8	14	100	Yes
	1130	+0.5	69.3	73.4	82	6	11	40	Yes
22	0815	+0.5	62.4	73.0	56	0	3	80	No
	1030	+0.2	61.8	73.6	52	0	0	80	No
	1245	+1.2	61.5	72.4	53	0.5	6	90	No
	1445	+1.3	60.9	72.1	52	2	2	80	No
23	0845	+0.3	65.0	73.0	65	0	0	90	No
	1315	−0.6	66.4	76.2	60	1	8	20	No
24	0820	+1.6	64.0	71.2	68	0	3	70	No
25	0845	+0.9	61.6	73.1	52	0	3	100	No
28	0845	+1.2	69.0	73.0	82	5	15	40	Yes
	1210	−0.2	71.1	76.0	78	6	11	80	Yes
	1340	+0.3	72.0	74.7	88	8	15	70	Yes
31	0820	+1.7	72.3	72.6	98	1	10	100	No
	1040	+1.2	72.0	72.2	98	1	11	100	No
	1230	−0.3	72.7	73.1	98	1	5	100	No
Sept. 1	1040	0.0	73.5	74.3	96	3	5	100*	Few
	1215	−0.6	74.0	75.4	93	4	13	100	Yes
	1445	−1.0	74.3	76.1	92	12	12	80	Yes
4	0915	+5.9	59.5	62.6	84	6	5	50	Yes
	1230	+6.0	59.5	62.6	84	6	3	25	Yes
7	0920	+1.0	64.0	70.1	72	4	10	0	No
	1055	+0.7	62.8	71.2	62	4	7	0	No

* Figures for clouds obtained from book (Sept. through Nov.)

Table 2.4.1. (Continued):

Month and Day 1950	Time EST	TEMPERATURES			Rel. humid. percent	Wind speed		Percent clouds	Streaks present
		Lake − air °C	Wet bulb °F	Dry bulb °F		Pond	Otis		
Sept. 7	1318	+0.5	62.8	71.8	61	6	10	0	Yes
	1512	+0.4	62.3	72.0	58	—	10	0	Yes
11	1015	+3.3	67.0	67.2	97	3–4	13	100	Yes
	1211	+3.4	66.9	67.1	97	2	14	100	Yes
	1431	+3.2	66.9	66.9	100	3	21	100	Yes
13	1032	+4.5	54.4	58.8	75	3	4	90	Yes
	1229	+3.4	54.9	60.8	68	2	6	80	Yes
	1429	+4.1	54.0	59.8	69	1	7	60	Yes
14	1010	+5.8	55.8	55.8	100	1–2	10	100	No
	1247	+5.0	57.8	58.8	94	1	8	99	Yes
15	1021	−0.5	64.0	67.0	85	4–5	19	99	Yes
	1221	−1.6	64.9	69.1	80	8	18	80	Yes
	1420	−1.0	65.5	68.0	88	12	12	50	Yes
18	0910	+1.7	53.7	63.0	54	0	0	0	No
	1105	+1.8	53.0	63.0	51	—	9	0	No
	1232	+1.1	54.0	64.0	52	4–5	9	0	No
	1430	+1.7	55.0	64.5	59	6–8	10	0	No
19	0906	+1.5	59.8	62.5	86	12–14	10	100	Yes
	1058	+0.6	60.0	64.0	79	15–18	14	100	Yes
	1247	+0.3	62.0	65.2	84	20	15	100	Yes
	1437	+0.7	61.0	64.0	85	18–20	12	100	Yes
21	0925	+1.7	57.0	61.4	76	4	7	20	No
	1118	+0.3	58.7	64.0	73	4	6	20	Yes
	1314	+0.8	56.0	63.9	61	4	6	0	No
	1425	−2.4	58.9	69.7	53	2	10	0	No
22	0915	+3.0	55.5	59.2	80	5–6	16	90	Yes
	1120	+3 1	55.3	58.8	81	4	13	100	Yes
	1307	+4.8	55.5	55.8	98	1	13	100	No
	1422	+4.8	55.2	55.8	97	1	12	100	No
26	0910	+0.2	57.1	62.0	74	1	0	100	No
	1115	+0.4	56.0	62.5	67	2	2	80	No
	1440	+1.2	52.8	59.9	63	2	5	90	No
30	1030	−4.0	63.5	69.0	74	1	0	100	No
Oct. 2	0950	−1.9	62.4	67.1	77	1	—	0	No
4	1005	2.5	53.6	58.4	71	12	—	100	Yes
6	—	1.4	52.0	59.1	63	2	—	0	No
11	1015	3.6	—	55.3	—	3	—	0	Few
16	1005	3.9	48.3	52.6	74	1	—	0	No
18	1000	.1	52.6	59.3	64	4	—	0	No
25	1035	−1.8	54.5	59.2	74	3	—	25	No
30	1020	1.9	49.1	52.6	78	5	—	100	Yes
Nov. 1	1010	−8.7	68.2	71.9	83	8	—	0	Yes
2	0955	−5.2	62.2	65.7	83	2	—	—	Yes
6	1022	−0.9	52.3	57.6	70	4	—	0	Yes
9	0925	0.9	52.6	54.5	88	5	—	100	Yes
11	—	7.2	34.6	39.7	60	6	—	0	Yes

2.4.5. SUMMARY OF DISCUSSION prepared by R. B. Montgomery

Mr. Ewing remarked on the surface film. Mr. McDonald and Mr. Thornthwaite called attention to gust patterns exhibited on water and on wheat fields.

2.4.6. DISCUSSION edited by R. B. Montgomery

MR. G. EWING: I should like to ask Mr. Stommel one question. I think it would be a good idea if you could find something the same about all these slicks. They all represent some kind of lateral compression of the surface film. There is always some kind of stress exerted on the sea surface where slicks are observed.

MR. H. STOMMEL: I think that is true of the slicks on the pond.

MR. J. E. MCDONALD: I want to ask a question of Mr. Stommel. There was a point in his film to which he didn't call attention that I thought was quite interesting from a turbulence point of view. I refer to the flecks of darkness which were visible in the gusts across the water.

MR. H. STOMMEL: There was one place in the picture where shadows of clouds were coming across.

MR. J. E. MCDONALD: No, I saw those. I wonder if there isn't a possibility of getting at the surface structure of an eddy from what those patterns exhibited. They seemed to be horseshoe shaped, reminiscent of Durst's findings at Cardington. They also appeared convex downwind.

MR. H. STOMMEL: I didn't notice that on the film. I wonder if Mr. Thornthwaite could tell us something about this. I think some people made visual observations of wheat fields and the like.

MR. C. W. THORNTHWAITE: There has been quite a bit of discussion about that. I remember — I am not sure that this is appropriate — 15 years ago in Oklahoma, we found a pattern of wind direction which shows the channeling of wind zones. There were high-wind zones paralleled by low-wind zones going along the wind direction. The zones might be a half-mile wide or a mile. That's far from the sea, in Oklahoma.

Contribution No. 558

International Symposium on Atmospheric Turbulence in the Boundary Layer
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GEOPHYSICAL RESEARCH PAPERS NO. 19

4.4. A RECORDING COMPUTER FOR THE DIRECT MEASUREMENT OF THE TURBULENT HEAT EXCHANGE IN THE ATMOSPHERE

D. PARSON, JR. and A. F. BUNKER

Woods Hole Oceanographic Institution [1,2]
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ABSTRACT

An instrument has been developed at the Woods Hole Oceanographic Institution which measures the instantaneous sensible heat exchange through a horizontal surface by the turbulent motions of the atmosphere. The instrument multiplies electronically the simultaneous signals from a bead thermistor, a hot-bead anemometer, and a horizontal-axis vane attached to a microtorque potentiometer. Heat flow values are summed over any given length of record with a ball-disc integrator. Values obtained are presented and compared with determinations from airplane temperature measurements. Confirmation of the validity on Priestley and Swinbank's objection to the basic assumptions used in the development of the classical diffusion equation is noted by plotting simultaneous values of the temperature against vertical velocity.

Massachusetts Institute of Technology, Geophysics Research Directorate
AIR FORCE CAMBRIDGE RESEARCH CENTER
Cambridge, Massachusetts
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[1] Contribution No. 558 from The Woods Hole Oceanographic Institution.

[2] This research was sponsored by the Office of Naval Research, under Contract No. N6onr-277, Task Order No. II, NR-082-021.

4.4.1. INTRODUCTION

The concept of the turbulent transport of properties by the atmosphere has been developed by summing the amounts of material or properties passing up or down through a horizontal surface.

The exchange is expressed by the following equation,

$$S = \frac{1}{Ft}\left[\sum m\uparrow s\uparrow \ - \sum m\downarrow s\downarrow\right] \tag{1}$$

in which m is the mass of a parcel, s the concentration of a property, F and t are the area and time interval. The small arrows indicate the direction of motion. Since in the past these small, individual mass and property exchanges were unobservable, Eq. (1) was developed further by Taylor [4] and Schmidt [3] to express the exchange in the more usable terms of the geometric distribution of a property. The differential diffusion equation,

$$S = -A\partial s/\partial z \tag{2}$$

introduces A, the coefficient of turbulent mass exchange. The value and variation of the coefficient with height, locale, and stability has been the object of numerous studies. The difficulty of determining a value of the exchange, S, which properly describes a given area has retarded the increase of our knowledge of the coefficient and its range of variation. The turbulent heat exchange computer described in this paper is an attempt to construct an instrument capable of detecting and recording the elements entering into the heat flow through a surface.

The basic notion of an instrument which could multiply the air temperature by the wind speed and the sine of the inclination of the wind thus yielding the heat flow was first suggested to the authors by Jeffries Wyman. Such an instrument observes the very elements that produce the heat flow and are the fundamental quantities used in the development of the diffusion equation.

One difficulty in the construction and use of the instrument is determining a size of vane and a lag of sensing elements and multiplying circuits that can respond to the variations causing the flow. The instrument constructed can only approximate the extremes of variation that the passing air presents, so the heat flow values determined cannot be exact. Further, it cannot be stated which range of eddy sizes or frequencies are instrumental in producing the bulk of the heat flow. The only certain way of determining whether the instrument can detect and compute the contribution to the heat flow of eddies within the critical range of sizes is to operate the computer in a region where the heat flow is known. Such an opportunity to test the equipment occurred in the summer of 1950, when airplane soundings were made by Joanne Malkus and Kenneth McCasland over Nantucket Island in connection with studies of convection, diffusion, and air flow over a heated island. From these temperature soundings which were made upwind, downwind, and over the island, the sensible heat flow into the atmosphere has been computed.

The diffusion equation (Eq. (2)) is based on the assumption that a parcel travels a distance l before mixing with its surroundings and that it possessed the concentrations s equal to the mean of s at the level at which it was last at rest. This assumption has been criticized by Priestley and Swinbank [2] on the grounds that mixing is a continuous process and that air parcels at rest have concentrations differing considerably from the mean. In the case of the property of temperature, they deduce that buoyancy forces will produce a component of the heat flow that is always upward. If this term is predominant, the flow will be upwards regardless of the sign of the temperature gradient. Since the instrument records both the temperatures and the vertical velocities of parcels, the data can be used to determine whether the parcels at rest vertically have individual temperatures equal to the mean or have temperatures distributed over several degrees either side of the mean.

4.4.2. DESCRIPTION OF THE TURBULENT HEAT EXCHANGE COMPUTER

4.4.2.1. *Detecting Elements*

The detecting elements of the instrument are a temperature element, an anemometer, and a small horizontal-axis vane. The temperature device is a ceramic bead thermistor whose electrical resistance is controlled by the temperature (Hales, [1]). The time constant of this resistor is 1.5 sec. The element is connected in a self-balancing bridge circuit (Fig. 4.4.1). To bring the variations on scale, the "Temp Zero" potentiometer is provided. In the present circuit, current through the thermistor element is kept at a low value, thus preventing any electrical heating which might affect the indicated temperature. Ganged with the bridge slide wire is a second potentiometer whose function will be explained later.

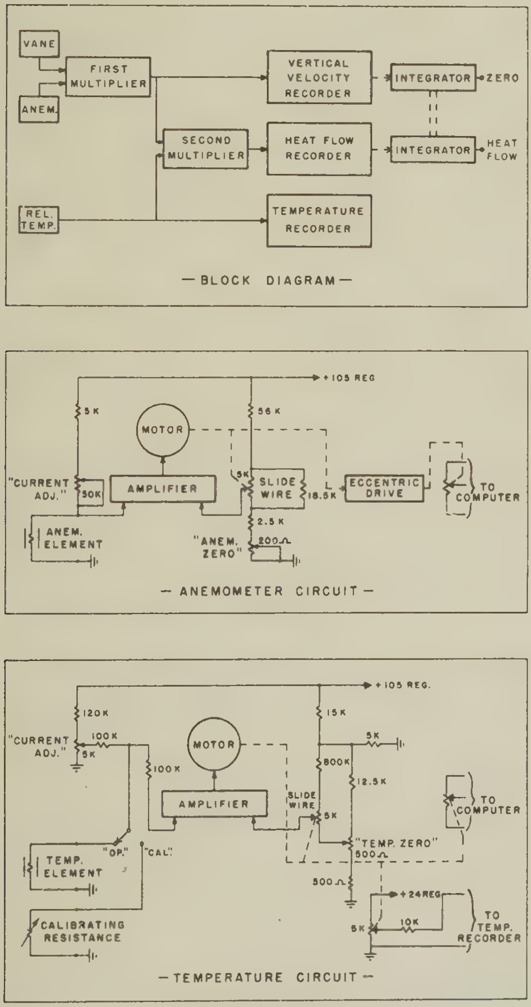
VANE
FIRST MULTIPLIER
ANEM.
VERTICAL VELOCITY RECORDER
INTEGRATOR
ZERO
SECOND MULTIPLIER
HEAT FLOW RECORDER
INTEGRATOR
HEAT FLOW
REL. TEMP.
TEMPERATURE RECORDER
— BLOCK DIAGRAM —
+105 REG
5K
56K
MOTOR
"CURRENT ADJ."
50K
AMPLIFIER
5K
SLIDE WIRE
18.5K
ECCENTRIC DRIVE
TO COMPUTER
ANEM. ELEMENT
2.5K
"ANEM. ZERO"
200Ω
— ANEMOMETER CIRCUIT —
+105 REG.
120K
"CURRENT ADJ."
100K
5K
MOTOR
15K
5K
100K
800K
12.5K
AMPLIFIER
SLIDE WIRE
5K
TO COMPUTER
"OP."
"CAL."
"TEMP. ZERO"
500Ω
TEMP. ELEMENT
500Ω
+24REG
CALIBRATING RESISTANCE
5K
10K
TO TEMP. RECORDER
— TEMPERATURE CIRCUIT —

Fig. 4.4.1. Block diagram of computer with detail of anemometer and temperature circuits.

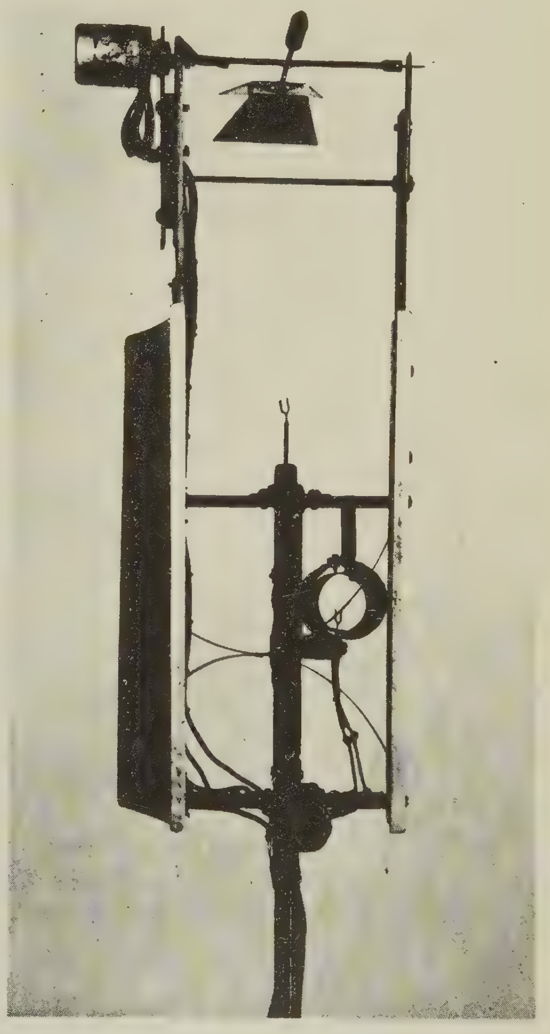

Fig. 4.4.2. Photograph of sensing unit showing horizontal-axis vane, shielded temperature element, and bead anemometer.

The signal from this circuit is not a linear function of temperature over the whole range of the element, but inasmuch as we are interested solely in the relative variations in a very limited portion of the range, this nonlinearity is unimportant.

The anemometer is also a bead thermistor. It is connected in a manner similar to the temperature element, except that the entire range is available without adjustment, and the bead is operated hot relative to the air. Here the ventilation, or rate of cooling, controls its resistance since the ambient temperature has but little effect (Hales, [1]). In the anemometer element, unfortunately, nonlinearity is not so easily dismissed. Here we are interested in absolute quantities, making it quite essential for the element to have a linear response. Linearity is attained through the use of an eccentric drive from the slide wire to the computing potentiometer. The shape of the eccentric was derived experimentally by exciting the element with known velocities and adjusting the curvature for linear output.

The vane which measures the inclination of the air stream consists of a small aluminum airfoil attached to a Giannini "microtorque" potentiometer and mounted on a horizontal axis. This vane and associated potentiometer produce a signal which is a linear function of the wind inclination.

The three elements are mounted on an assembly (Fig. 4.4.2) which is free to swing about a vertical axis. The assembly employs a tail vane whose purpose is to keep the whole unit headed into the wind. The vane, when set upon a tripod, is about 2 m above the ground.

4.4.2.2. *Computing Circuits and Recorders*

The function of the instrument is based upon the following heat transport equation:

$$F = \frac{c_p\bar{\rho}}{t}\left(\sum_0^t w'T'\right) = \frac{c_p\bar{\rho}}{t}\left[\sum_0^t (u' \sin\theta')T'\right] \tag{3}$$

where F is the heat flow per unit time and area, w' the instantaneous vertical velocity, u' the instantaneous total velocity, θ' the instantaneous inclination of the wind, T' the instantaneous temperature of an air parcel, t the time interval of the observations, and c_p and $\bar{\rho}$ the specific heat and average density of the air.

The first computation made is the multiplication of the total speed of the air by the sine of the inclination to give the vertical velocities. See the block diagram, Fig. 4.4.1. This multiplication is accomplished by means of cascaded potentiometers connected as shown in Fig. 4.4.3. The vane is connected to two sources of potential so as to produce a positive or negative potential as governed by the position of the vane. This potential is applied to the anemometer controlled potentiometer, the output of which then is a measure of the vertical velocity. Variable loading on the vane potentiometer is minimized by making the anemometer potentiometer resistance relatively high.

The vertical velocity signal from the anemometer is amplified by two d-c amplifier stages and applied through a potentiometer ("Veloc amplitude" adj) to an Esterline-Angus milliammeter recorder. The function of this potentiometer is to make the velocity recorder reading commensurate with that of the heat flow recorder. Drift in these stages is of no consequence.

Since the sine of the small angles normally encountered is nearly a linear function of the angle, the vane is attached to a linear potentiometer rather than to a sine function potentiometer.

Referring to the block diagram, Fig. 4.4.1, it is seen that the vertical velocity signal branches: one branch leads to the recorder mentioned above while the other branch leads to a second multiplication circuit. This circuit multiplies the signals of the velocities by the temperature variations to give the heat flow which is then recorded. The signals are multiplied by connecting to the power stage (Fig. 4.4.3) a potentiometer driven by the temperature bridge-balancing motor. The output of this potentiometer is proportional to the product of the temperature by the vertical velocities and hence gives the instantaneous heat flow. This completes the description of the computer. Integration of the heat flow is carried out from the records of the vertical velocities and the heat flows.

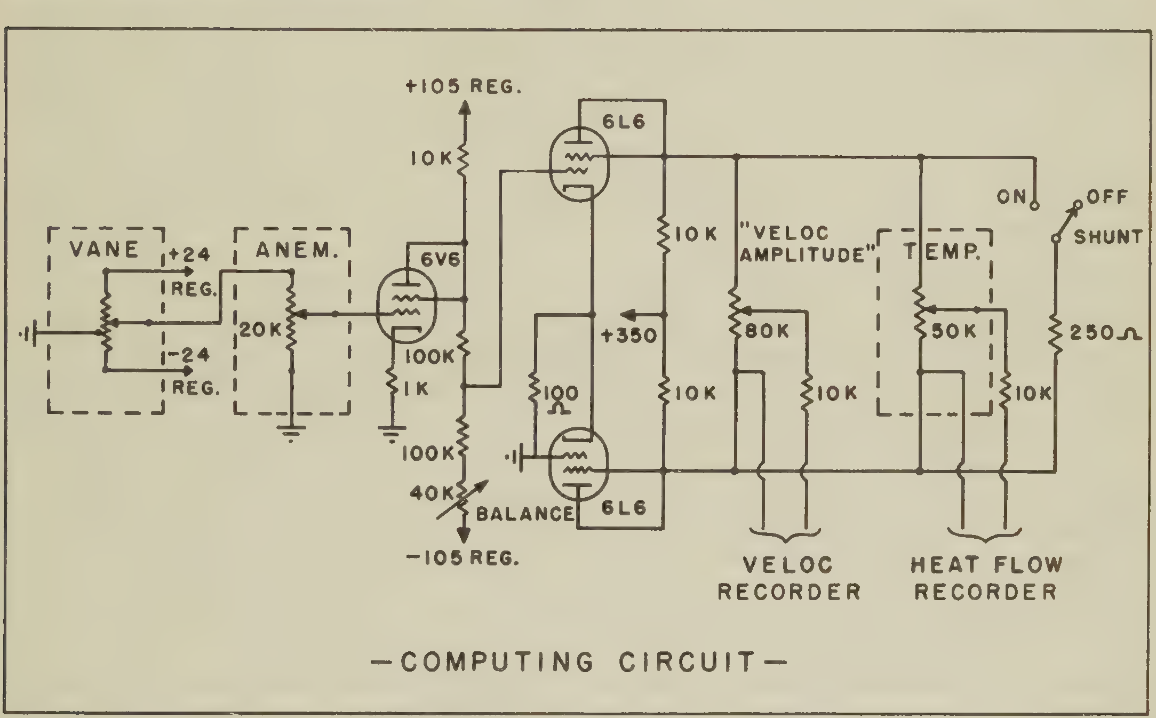

Fig. 4.4.3. Detail of computing circuit.

4.4.2.3. *Integration and Operation of the Instrument*

Instantaneous values recorded on the charts are summed with a ball-disc integrator. The integrator is in effect a variable speed device whose output is proportional to the speed of the disc and to the position of the balls. If the disc is caused to rotate at a rate proportional to the chart time, and if the balls are positioned by the chart trace, then the total registered by the output counter will be a measure of the area included under the chart trace.

It is immediately apparent that the proper evaluation of the heat flow record depends upon the summation of the mass transport being equal to zero. In practice a sum equal to zero can rarely be attained, since many hours would be consumed trying to adjust the tilt of the detecting vane so that the velocities would add up to zero. Accordingly, the instrument has been designed without concern for the absolute vertical, that is, the vertical component is not measured in absolute terms with respect to the direction of gravity. Rather it is more convenient, and also more significant, to assume that the summation of the vertical components must equal zero over a given time, and to adjust, with an additive term, all the individual recorded values so that this does occur. In this way the surface through which the transport is being measured is oriented parallel to the plane of flow of the air. The process is more clearly expressed by the following equations. The assumption is made that

$$\bar{\rho}\,\bar{w} = \bar{\rho}\sum w'/n = 0 \tag{4}$$

for a sufficient number of measurements of w'. Whenever the instrument is not set up vertically or an up or downslope wind is being measured

$$\bar{\rho}\sum w'/n = \bar{w}_{\text{obs}}\,\bar{\rho} \neq 0. \tag{5}$$

By subtracting $\bar{w}_{\text{obs}}$ from the individual values

$$\bar{\rho}\sum(w_1' - \bar{w}_{\text{obs}}),\quad (w_2' - \bar{w}_{\text{obs}}),\quad \ldots (w_n' - \bar{w}_{\text{obs}})/n = 0 \tag{6}$$

the reference surface for diffusion is made parallel to the plane of flow. By orienting the surface in this manner, advective contributions to the heat flow are eliminated. A mechanical means of subtracting $\bar{w}_{\text{obs}}$ will be described later.

The computer produces a record of the instantaneous values of $c_p\bar{\rho}(\bar{w} + w')(T')$, where T' is the deviation from an arbitrary zero temperature, usually 1° or 2°C below the lowest value of T'. It is necessary to eliminate the $\bar{w}T'$ term from the product to obtain the turbulent heat transport. The method of accomplishing this elimination can now be demonstrated. The operation of the instrument in the field is as follows. After the vane is set up in the wind so that $\bar{w}$ is small, the temperature zero is adjusted so that T' is always positive. The instrument is run for about 5 min, obtaining values of $\bar{w} + w'$, T', and $\bar{w}T' + w'T'$. After this run, another is made with the temperature "fixed" at the average temperature, T', by substituting a constant resistance for the variable resistance of the thermistor. The resulting traces when integrated later are used to correct any inequalities in the recorders and to subtract the $\bar{w}T'$ term from the heat flow record.

The application of the ball-disc integrator to the four records can now be described with the aid of Fig. 4.4.4. The chart is moved past a stylus at a rate which can be adjusted to suit the operator. The chart drive is coupled directly to the integrator disc thus causing the disc speed to be a function of time. By moving the handle, the operator positions the stylus on the trace, following it as the chart moves. Since the chart is recorded with a curved "Y" coordinate, the stylus arm length is made exactly equal to that of the recording pen.

The "displacement linkage" is shown schematically in Fig. 4.4.4. Basically, it consists of four concentric elements inserted between the stylus arm and the rack and pinion drive to the integrator balls. Each element takes the form of a wafer, each of whose center hole encompasses the shaft which connects to the integrator balls and operating handle, the whole assembly moving with the handle. The angular position of the "stylus wafer" relative to that of the "displacement wafer" is controlled by the "zero adjustment" and associated spring. Thus, with other elements undisturbed, the position of the trace is in effect varied by the "zero adjustment."

The "displacement wafer" is linked to the "output wafer" through the spring loaded equalizer stop screw or the fixed stop screw, depending on the position of the shift lever. If the lever is switched to "Heat Flow" the equalization adjustment becomes active, and operates similarly to the "zero adjustment."

Thus we have in effect a control over the average value of the heat flow trace relative to that of the velocities trace, and an over-all control which varies both by the same amount. The two adjustments are arranged so that their effects are cumulative.

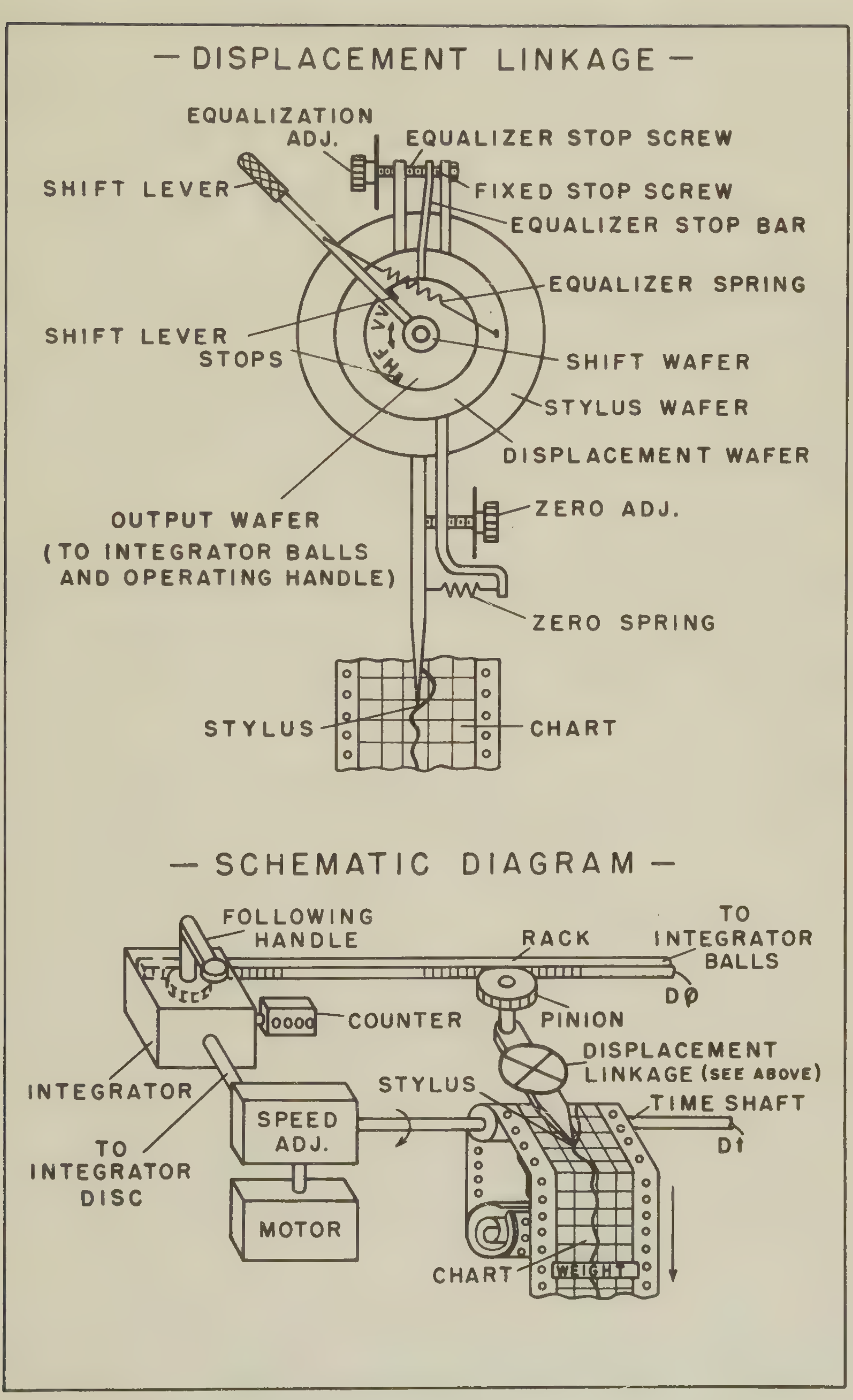
— DISPLACEMENT LINKAGE —
EQUALIZATION ADJ.
EQUALIZER STOP SCREW
SHIFT LEVER
FIXED STOP SCREW
EQUALIZER STOP BAR
EQUALIZER SPRING
SHIFT LEVER STOPS
SHIFT WAFER
STYLUS WAFER
DISPLACEMENT WAFER
ZERO ADJ.
OUTPUT WAFER (TO INTEGRATOR BALLS AND OPERATING HANDLE)
ZERO SPRING
STYLUS
CHART
— SCHEMATIC DIAGRAM —
FOLLOWING HANDLE
RACK
TO INTEGRATOR BALLS
DΦ
COUNTER
PINION
DISPLACEMENT LINKAGE (SEE ABOVE)
INTEGRATOR
STYLUS
TIME SHAFT
SPEED ADJ.
Dt
TO INTEGRATOR DISC
MOTOR
CHART
WEIGHT

Fig. 4.4.4. Construction of displacement linkage.

The following operation of equalization serves to eliminate systematic errors in the two channels, and allows the subtraction of $\overline{wT'}$ from the record of $\overline{w}T' + w'T'$.

(a) The vertical velocity record for the first run is placed on the integrator and measured. The "zero adjustment" dial is turned so that subsequent measurements of the trace yield zero.

(b) The vertical velocity record for the second run is placed on the integrator and measured until a point is reached near the end of the run at which the summation of the vertical velocities equals zero.

(c) The corresponding point on the heat flow record obtained with the fixed temperature is located. This length is integrated and set equal to zero by turning the "equalizer" dial. The displacement of the linkage now represents $-(\overline{wT'}$ + systematic errors).

(d) The heat flow record obtained with the variable temperature is placed on the integrator and measured. The final result on the counter at the end of the run represents the desired $\overline{w'T'}$ free of systematic errors. If later calculation shows that $T_{\text{fixed}} \neq \overline{T}'$, then a correction term $\overline{w}(\overline{T}' - T_{\text{fixed}})$ must be added.

4.4.2.4. *Accuracy Specifications*

No attempt to define the accuracy of this instrument has been made from an analysis of its component parts. The dynamic response and damping of the detecting vane is undetermined and it was deemed inadvisable to expend the time and effort to determine it either theoretically or experimentally. The same holds true for the various electrical and mechanical units involved. The two servomechanisms used in the anemometer and temperature circuits introduce time lags which further complicate the analysis of errors, as does also the movement of the recorders.

Instead of carrying out a detailed analysis and synthesis of errors and time lags, it was decided to compare the results from this instrument with those yielded by a completely different system of measurement. A discussion of this work and the results obtained is presented below.

4.4.3. HEAT FLOW MEASUREMENTS

The computer has been used to measure heat flows on several days when simultaneous observations of the temperature made from an airplane were available. The sounding airplane, equipped with a recording psychrograph, made four ascents in the vicinity of Nantucket Island. One helical ascent was made 2 km upwind from the island, another over the center of the island, another about 2 km leeward of the island, and the last 8–10 km leeward. Heat flows have been computed from the accumulation of heat in the atmosphere as the water-cooled air blew over the warmer island. Flows measured in this manner were compared with the computer results. The good agreement between the two determinations indicates that the size and damping characteristics of the vane, the lags of the thermal elements, and the lag of the multiplying circuit introduce no serious error into the heat flow calculation.

Table 4.4.1 has been prepared to present the measured values. The first column, after the date of the observation, gives the heat flow value determined by the computer expressed in cal/cm^2 sec. Three values of the flow determined from the airplane soundings are presented next. The first column under the heading gives the average heat flow over the first 2 or 3 km of heated land. The second column represents the average over 3–5 km of land plus 1–2 km of cooler water. The last is the average over 4–8 km of cooler water.

Table 4.4.1. Heat flow computations.
(cal/cm^2 sec)

Date	Heat exchange computer	Airplane observations 1–2	2–3	3–4
9 Aug. 1950	$+3.5 \times 10^{-3}$	$+10 \times 10^{-3}$	$+6.3 \times 10^{-3}$	-16×10^{-3}
14 Aug. 1950	$+7.8 \times 10^{-3}$	$+14 \times 10^{-3}$	$+1.9 \times 10^{-3}$	-1.2×10^{-3}
28 Aug. 1950	$+6.5 \times 10^{-3}$	$+4.7 \times 10^{-3}$	$+9.1 \times 10^{-3}$	$+0.7 \times 10^{-3}$
5 Sept. 1950	$+22 \times 10^{-3}$	$+8.8 \times 10^{-3}$	$+4.8 \times 10^{-3}$	-0.2×10^{-3}
Average	$+10.0 \times 10^{-3}$	$+9.4 \times 10^{-3}$	$+5.5 \times 10^{-3}$	-4.2×10^{-3}

Since the computer was operated at the North Nantucket Airport about 3–4 km from the windward shore (in most cases), it is to be expected the computer values would agree best with the first column of the airplane observations as, indeed, they do.

A scatter diagram, Fig. 4.4.5, of individual vertical velocities of the turbulent air plotted against simultaneous temperature readings shows the validity of Priestley and Swinbank's objection to the assumption

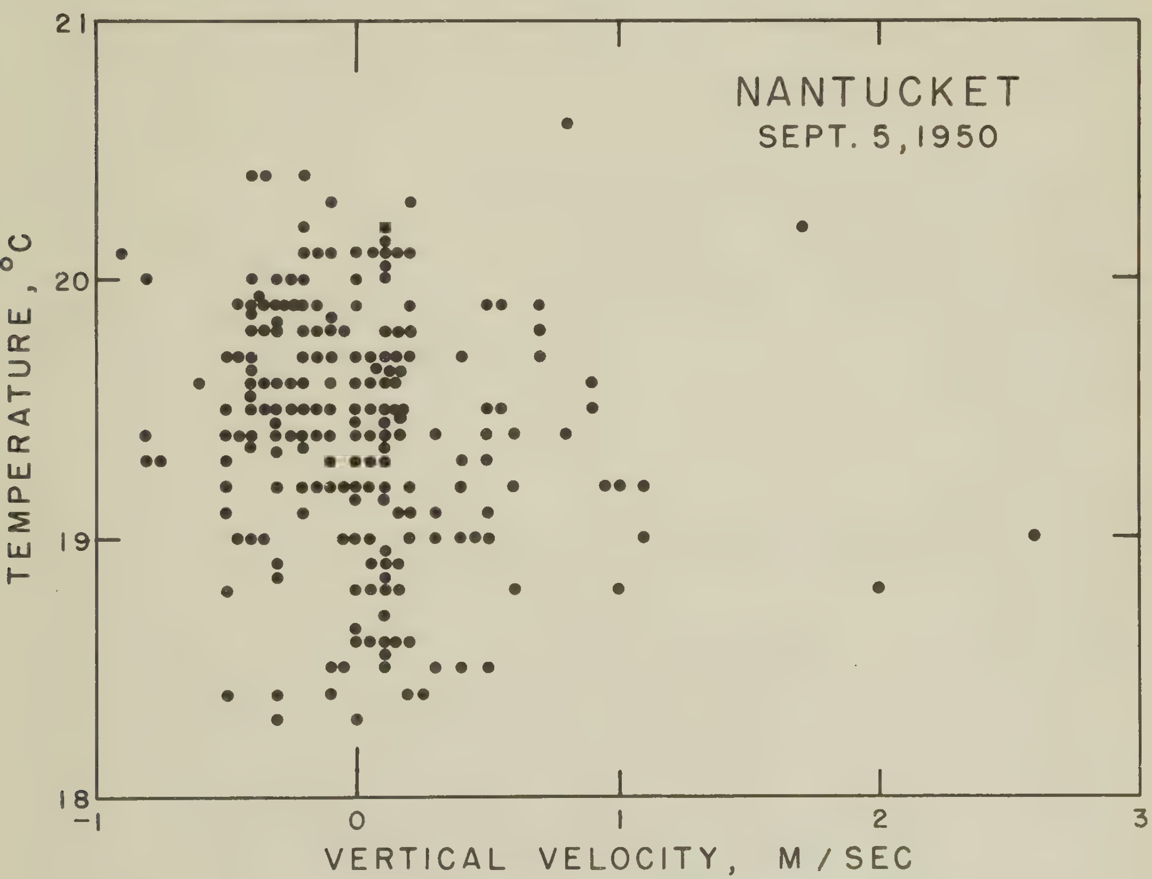

Fig. 4.4.5. Vertical velocity-temperature diagram.

underlying the diffusion equation. It is clear that the temperature of the parcels with zero vertical velocity varies considerably from the mean as they reasoned that it must. No further test of their theory has been made to date with the computer, although it may be used to establish the relation between a stable lapse rate and the heat flow.

Another feature brought out by the diagram is the asymmetry of the velocities about the zero point. Downdrafts seem to be restrained to velocities less than 0.9 m/sec while updrafts reach maximum velocities of 2.6 m/sec. A similar pattern is obtained with the vane inverted, indicating the reality of the asymmetry which is presumably associated with the proximity of the ground.

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4.4.4. SUMMARY OF DISCUSSION prepared by C. H. B. Priestley

The discussion was concerned with questions of error. The approximation of vertical velocity by a linear rather than a sine function of angle was being remedied, and effects of variations of ambient air temperature eliminated. This, however, would not remove the uncertainty of the gradient as measured by a single sounding. The source of error emphasized by Mr. Swinbank, inadequate elimination or inexact repetition of the mean value, was again referred to.

4.4.5. DISCUSSION edited by C. H. B. Priestley

MR. P. H. LOWRY: I noticed that you used a linear function of angle rather than a sine function. I was wondering if you might indicate what sort of an error would be involved.

MR. A. F. BUNKER: That is another approximation incorporated in the computer. It probably didn't affect the results too much. Some of the inclinations do reach 30°. When you get into these greater angles, there is a departure from linearity, of course, but I don't think that it materially affects the heat flow.

MR. J. E. MCDONALD: What are the probable errors that you might have in the airplane flux measurements?

MR. A. F. BUNKER: I haven't computed probable errors. We took only one sounding at each place and that, in itself, is a source of error, for the lapse rate and the individual temperatures that you measure do vary radically from one moment to the next. You should take several soundings to obtain reliable averages.

As far as the instrumental errors are concerned, the errors are very low — probably a tenth of a degree centigrade. We should have taken more soundings, but there wasn't time for it, so there is an appreciable probable error although I haven't determined it.

MR. W. C. SWINBANK: I would like to raise a point on this question of errors. It was not clear from what Mr. Bunker said whether the possible source of error that I referred to earlier this morning does not occur in his analysis. As I understand it, he transfers his mean from one integrator to another and, unless this is done with extreme accuracy, a large error must thereby be introduced.

MR. A. F. BUNKER: We used the same integrator all the time, and we put the different traces on that one integrator. We made sure the two recorders and different channels were identical in that way.

(Note added later by authors): Modifications to the computer are being made as a result of the discussions both in and outside the meetings and of the recent paper by E. R. Sanford (*J. Meteor.*, 8, 182–190, 1951) on thermistor anemometry.

A sine function potentiometer is being built into the circuit to eliminate the previously mentioned approximation in the vertical velocity computation. Also, a temperature compensator is being added to the anemometer circuit to eliminate the effect of variations of the ambient air temperature.

Contribution No. 561

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PROCESSES CONTRIBUTING TO THE DECREASE OF COLIFORM BACTERIA IN A TIDAL ESTUARY[1]

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Introduction

It has long been known that coliform bacteria introduced into tidal waters disappear rapidly so that the numbers decrease from many thousands per ml. in the region where the water is practically fresh to very few, or none at all, where the water approaches a salinity characteristic of sea water. Many factors have been postulated to account for such pronounced decreases, but their relative importance has never been quantitatively assessed.

Dilution of the river water with sea water is important, but it is not sufficient to explain the enormous decreases that are observed. ZoBell (1936, 1946), Ketchum *et al.* (1949), and Vaccaro *et al.* (1950) have pointed out the importance of the bactericidal action of sea water. The zooplankton in the water remove organisms and particulate matter from the water which they filter, and Fuller (1937) and Harvey (1937) have evaluated the effective filtration rate. Weiss (1951) has studied the adsorption of *E. coli* on river and estuarine silts, and his results suggest that sedimentation may deposit many of the coliform bacteria on the bottom.

A quantitative evaluation of these various factors is possible only when the circulation and exchanges of the fresh and salt water in the estuary are known. With a knowledge of the circulation, direct calculation of the effect of dilution can be made, and the effects of bactericidal action and of predation by zooplankton can then be evaluated.

This paper presents an interpretation of observations made in the Raritan River, New Jersey. It is shown that the observed distribution of coliform bacteria within the tidal reaches of the Raritan River closely approximates the distribution to be expected as a result of the cumulative effects of the bactericidal action of sea water, predation by zooplankton and dilution.

Distribution of Properties

On June 26 and 27, 1949, surveys of the Raritan River were made, during

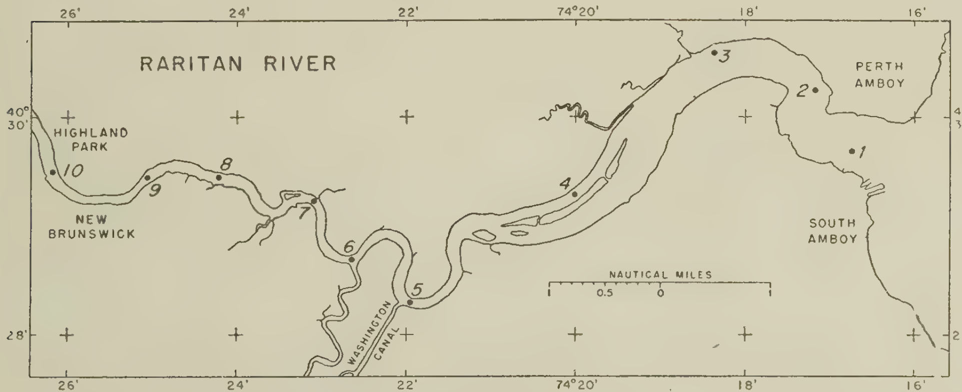

Fig. 1. Chart of Raritan River showing location of stations occupied during the survey.

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[1] Contribution No. 561 from the Woods Hole Oceanographic Institution. This investigation was supported, in part, by research grants from the Division of Research Grants and Fellowships of the National Institutes of Health, U. S. Public Health Service.

which time eight stations were occupied within an hour of low tide, and ten stations were occupied within an hour of high tide. The location of these stations is shown in Figure 1.

The surface distribution of salinity and temperature was obtained using a salinity-temperature-depth recorder (Jacobson 1948). At each station a record of vertical distribution was obtained by lowering the measuring elements of this instrument to the bottom. Since the water in the river was generally stratified vertically, water samples and plankton tows were taken both above and below the halocline. Nansen bottle samples were analyzed for

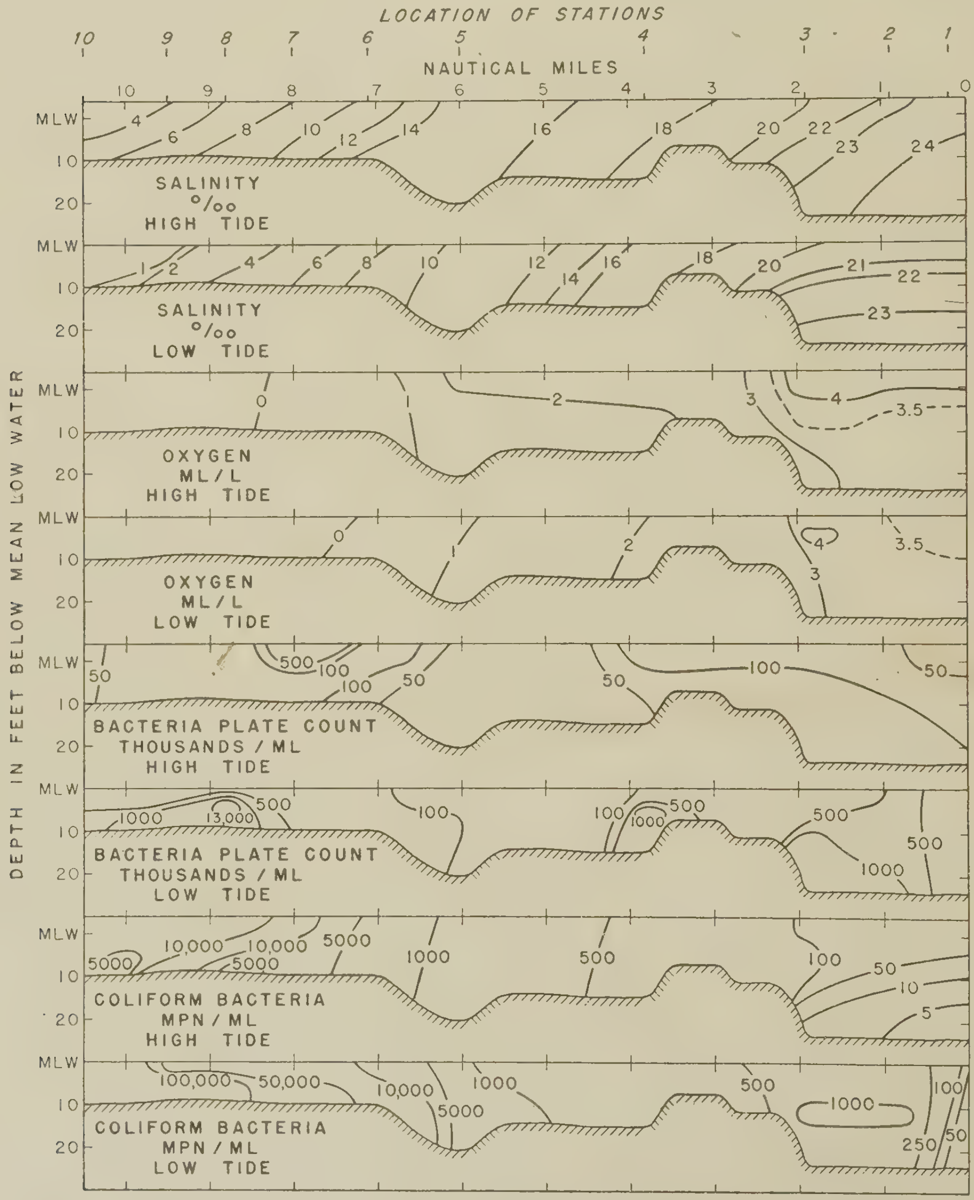

Fig. 2. Distributions of properties in a longitudinal section of Raritan River at high and at low tides.

oxygen and salinity. The plankton tows were collected with a Clarke-Bumpus (1950) sampler using a No. 2-mesh net. The volume of water filtered during each tow was recorded.

Bacteriological samples were obtained with a modified ZoBell (1941) type water sampler at two or more depths at each station. A portion of each sample was plated for total bacterial counts on salt water nutrient agar (Reuszer 1933). These plates were counted after seven days. Coliform presumptive tests were made in triplicate in at least three dilutions, using lauryl sulfate Tryptose broth tubes ("Standard Methods," 1946). They were not confirmed or completed so that the discussion of coliform bacteria in this paper is not restricted to *Escherichia coli.* Oxygen concentration was measured by the Winkler method ("Standard Methods," 1946). The reagents for the oxygen analysis were added immediately after the collection of the sample. The titrations were done ashore. The bacteriological work was all done ashore, the samples being kept on ice until they could be treated, which was always accomplished within fifteen hours after collection.

Dr. Willem Rudolfs of Rutgers University kindly made available the facilities of his laboratory during our survey, and his cooperation is most gratefully acknowledged.

The distributions of properties observed at high and at low tide are shown in Figure 2. In these, and in subsequent figures, the distance scale is measured from the mouth of the river at Perth Amboy.

Near New Brunswick the salinity of the water was always low (less than 4 $^{0}/_{00}$). The source of the sea water in the area is a mixture of Hudson River water and sea water having a salinity of 27 $^{0}/_{00}$. The salinities observed at New Brunswick indicate that the water at this location contained between 85 and 96 per cent Raritan River water. The salinity gradually increased so that at Perth Amboy it was 21 to 24 $^{0}/_{00}$, giving concentrations of 22 to 11 per cent Raritan River water.

There was no measurable oxygen in the water at New Brunswick but the concen-

TABLE I. *Distribution of zooplankton in the Raritan River at high tide (numbers per liter of water)*

Miles from river mouth	Station	Cladocera	Protozoa and flagellates	*Acartia tonsa*	*Oithonina nana*
10.5	10 a	No living zooplankton			
	b	No living zooplankton			
9.5	9 a	No living zooplankton			
	b	No living zooplankton			
8.8	8 a	.18	.04		
	b	0	0	.07	
7.1	6 a	0	0	.58	
	b	0	0	2.50	
6.0	5 a	0	0	20.45	.80
	b	.33	0	44.6	1.67
6.0	5 b	.59	0	54.62	1.76
3.8	4 a	0	0	17.11	.76
	b	.21	0	33.24	3.43
0.25	1 a	0	0	31.44	.19
	b	.08	0	56.22	6.39

Note: a and b represent tows above and below the halocline.

TABLE II. *Distribution of zooplankton in the Raritan River at low tide (numbers per liter of water)*

Miles from river mouth	Station	Cladocera	Protozoa and flagellates	*Acartia tonsa*	*Oithonina nana*
10.5	10 b	0	.087	0	0
8.8	8 a	0	.016	0	0
	b	0	0	0	
7.1	6 a	0	0	0	0
	b	.033	0	0	0
6.75	a	0	0	.05	0
	b	.34	0	.34	0
6.0	5 a	0	0	.056	0
	b	.39	0	.69	0
6.0	5 a	0	0	0	0
	b	.03	0	.23	0
3.8	4 a	0	0	16.7	.91
	b	.98	0	111.71	7.67
0.25	1 a	0	0	0	0
	b	0	0	48.7	6.4

Note: a and b represent tows above and below the halocline.

tration of oxygen increased down river so that, at Perth Amboy, it was 65 to 75 per cent of the saturated value.

The total counts of bacteria remain nearly the same throughout the length of the river, though there was considerable variation in the numbers observed with depth. The coliform bacteria decreased from maximum values of 110,000 per ml. at New Brunswick to average values of less than 100 per ml. at the river mouth.

There were no living zooplankton in the water containing zero oxygen in the neighborhood of New Brunswick. Near the mouth of the river the zooplankton population was fairly high (more than 100 organisms per liter) and was made up of relatively few species, *Acartia tonsa* being predominant in all collections. The numbers of various species of zooplankton observed above and below the halocline at various locations are given in Tables I and II.

THEORETICAL CONSIDERATIONS

The primary objective of this investigation was to evaluate the effects of the various processes mentioned above in decreasing the population of coliform bacteria in the tidal reaches of the river. The technique which has been followed is based upon the concept that the population of coliform bacteria to be expected at any location within the tidal reaches of the river depends upon the original population in the undiluted river water which is progressively decreased by the bactericidal action of sea water, predation and dilution as the water traverses the estuary.

As the coliform bacteria are being transported downstream by the circulation of the water they are subjected to the bactericidal action of sea water. The number of coliform bacteria remaining in a given sample of water after taking account of this process is given by:

$$C_t = C_0 e^{-kt} \qquad (1)$$

in which C_0 and C_t are respectively the original count and the count after time t, and k is the coefficient of death rate.

The consumption of bacteria by zooplankton may be described in a similar way. Fuller (1937) has shown that the expected number of cells remaining in a given sample of water at the end of time t can be expressed by the equation:

$$C_t = C_0 e^{-wpt} \qquad (2)$$

in which w is the volume of water filtered per unit time, and p is the number of predators per unit volume.

These two equations may be combined to show the joint effects of mortality and predation as follows:

$$C_t = C_0 e^{-t(k+wp)} \qquad (3)$$

While the population of coliform bacteria is being decreased by the bactericidal action and by predation, the water is moving down the estuary and mixing with progressively greater amounts of sea water. It is necessary, for two reasons, to define the circulation and exchanges of the water quantitatively. The rate of the circulation determines the length of time the population is exposed to the bactericidal action and to predation, and the dilution of the population is a direct consequence of the mixing of the fresh and salt waters.

An empirical theory which describes the circulation and exchanges of fresh and salt waters in tidal estuaries has been previously presented (Ketchum 1951). This theory permits the computation of the quantity of river water present in any part of the estuary and the length of time various proportions of the river water have been present within that part of the estuary. The application of the theory requires the subdivision of the estuary into volume segments defined horizontally by the width of the estuary and by the mean excursion of a particle of water on the flood tide. The quantity of water removed from such a segment on each tidal cycle is given by an exchange ratio derived from the volumes of water present at high and at low tides. The total quantity of river water accumulated Q_n in any segment n is a mixture of water of various tidal ages, so that:

$$Q_n = R[1 + (1 - r_n) + (1 - r_n)^2 + (1 - r_n)^3 + \cdots + (1 - r_n)^m] \quad (4)$$

in which r_n, the exchange ratio, is the ratio of the intertidal volume to the high-tide volume of the nth segment, R is the volume of water introduced by the river during a complete tidal cycle, and the superscripts 1, 2, 3 $\cdots$ m refer to time in units of tidal cycles. As m approaches infinity this series approaches:

$$Q_n = \frac{R}{r_n} \quad (5)$$

If dilution were the only process active in decreasing the coliform population, the steady-state population, C_n, expected in the nth volume segment, could be obtained by multiplying the original concentration of bacteria in the undiluted source river water, C_0, by the average fraction of fresh water, F_n, in the segment, that is:

$$C_n = C_0 F_n \quad (6)$$

The average fraction of fresh water is given by the ratio between Q_n, the quantity of river water accumulated (equation 4), and the high-tide volume of the segment. It can also be computed from the salinity data of an hydrographic survey.

Before combining the biological and the circulation equations, however, the initial population of each segment must be expressed in terms of the concentration of bacteria entering that segment during each tidal cycle. This is necessary because, in traversing the estuary, the coliform population is reduced not only by dilution, as in equation (6), but also by the cumulative effects of the bactericidal action and predation in all of the intervening landward segments. The population entering the nth segment, $(C_0)_n$, is related to the population in the adjacent landward segment C_{n-1}, by the relationship:

$$(C_0)_n = C_{n-1} \frac{F_n}{F_{n-1}} \quad (7)$$

If dilution were the only process reducing the population, C_n would equal $(C_0)_n$ in each segment.

Each term within the brackets of the circulation equation (4) shows the proportion of water which has been within the segment for the period of time indicated by the superscripts. The biological processes have been reducing the bacterial population during the same period of time. The equations for the circulation (4) and for the biological processes (3) can be combined if time is expressed in units of tidal cycles, and if $(C_0)_n$ is substituted for the original population and C_n for the final population in equation (3).

$$Q_n C_n = R(C_0)_n[1 + (1 - r_n)e^{-(k+wp)} + (1-r_n)^2 e^{-2(k+wp)} + (1-r_n)^3 e^{-3(k+wp)} + \cdots + (1-r_n)^m e^{-m(k+wp)}] \quad (8)$$

This series approaches:

$$C_n = (C_0)_n \frac{R}{Q_n} \frac{1 - (1 - r_n)^m e^{-m(k+wp)}}{1 - (1 - r_n) e^{-(k+wp)}} \quad (9)$$

Since $(1 - r)^m$ and $e^{-m(k+wp)}$ both approach zero as the number of tidal cycles m approaches infinity, and since R/Q_n equals the exchange ratio, r_n, equation (9) may be reduced to:

$$C_n = (C_0)_n r_n \frac{1}{1 - (1 - r_n) e^{-(k+wp)}} \quad (10)$$

From this equation one can calculate the joint effects of dilution, bactericidal action and predation in decreasing the number of coliform bacteria down the length of the tidal estuary.

The relative importance of the various processes can be assessed by making the computations in sequence. For example, the effect of dilution alone can be computed by assuming k and wp to be zero, in which case $e^{-(k+wp)}$ becomes unity, the exchange ratio cancels out, and equations (7) and (10) are combined to give the dilution effect:

$$C_n = C_{n-1} \frac{F_n}{F_{n-1}} \quad (11)$$

The combined effects of dilution and bactericidal action can be calculated from equation (10) by assuming wp to be zero, when the bactericidal mortality becomes the only biological process considered. The time factor is inseparable from the circulation equation so that it is not possible to compute the biological effects alone.

The calculations described above are applicable to the high-tide distribution. The expected distribution at low tide can be most simply derived from the changes in location of the water as the tide ebbs. The estuary is segmented in such a way that the high-tide volume of each segment is equal to the low-tide volume of the adjacent seaward segment (Ketchum 1951). As a first approximation, therefore, the ebbing tide moves the water throughout the estuary one segment seaward. The populations at low tide are taken as equal to the population expected in the adjacent landward segment at high tide decreased by the predation and mortality due to bactericidal action which occur during a half tidal cycle. The empirical theory upon which these calculations are based assumes

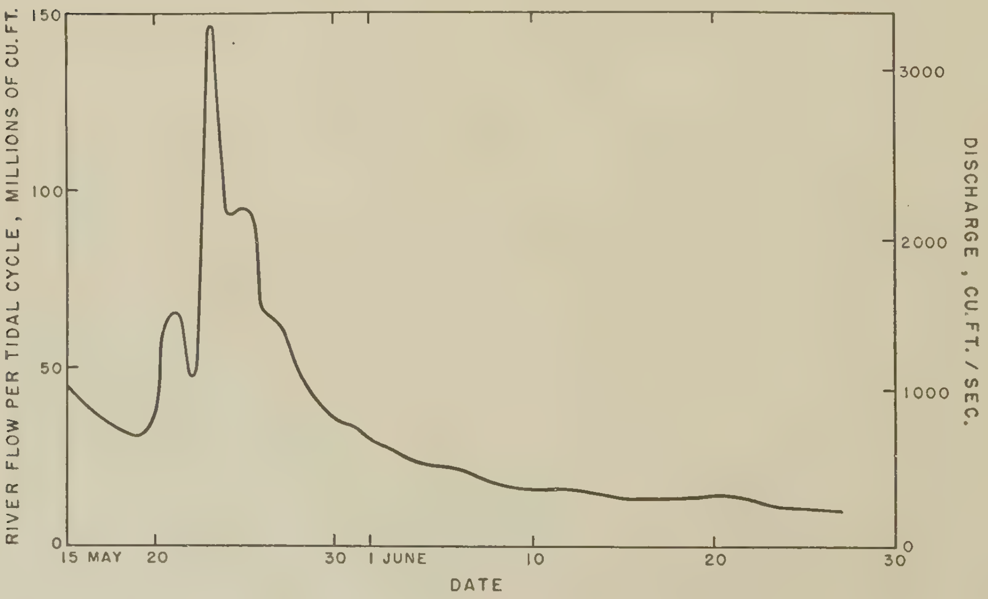

FIG. 3. River flow of the Raritan River during and prior to the time of the survey.

TABLE III. *The volumes of water, exchange ratios, and escaping volumes of river water for the various tidal excursion segments within the Raritan River*

Segment	Distance, miles*	Intertidal volume 10^6 ft.^{3}	High tide volume 10^6 ft.^{3}	River water volume 10^6 ft.^{3}	Exchange ratio r	Escaping volume fresh 10^6 ft.^{3}
1	11.77	16	20	18	0.80	14.5
2	10.10	30	50	42	0.60	25.2
3	8.10	39	89	60	0.44	26.4
4	6.20	46	135	66	0.34	22.4
5	4.53	65	200	74	0.325	24.1
6	2.75	130	330	86	0.39	33.6
7	0.9	220	550	98	0.40	39.2
8	0	274	774	113	0.354	40.0

* Distance from the river mouth to the center of the segment.

that the water in each volume segment is completely mixed at high tide. It will be recognized that this way of determining conditions at low tide does not take account of any additional dilution during the ebbing tide. As a first approximation this does not introduce any serious discrepancy in the results.

APPLICATION

Flushing of the estuary. Prior to the time of our survey the river flow was not constant, but decreased from a volume of 147 million cubic feet to a volume of 10.4 million cubic feet per tidal cycle. These river flow data are presented in Figure 3. Under such conditions a different volume of water will be moving through successive cross sections of the estuary. When the results of an hydrographic survey are available, however, one can compute the quantity of river water in each tidal-excursion segment (Tully 1949; Ketchum 1950). By applying the exchange ratio the volume of river water escaping through each cross section on the tidal cycle at the time of the survey can be estimated. This escaping volume of river water is, then, substituted for R in the equations. The necessary data for these calculations are given in Table III for the Raritan River at the time of our survey. The escaping volume of water was nearly constant throughout most of the length of the river, but it was lowest at the innermost segment, and highest at the mouth of the river. This variation would be expected from the change in river flow with time shown in Figure 3.

Bacterial population. In spite of the inherent variability of bacterial counting techniques, it is clear, from our data as shown in Figure 2, that the coliform population decreased from about 100,000 per ml. at the New Brunswick end of the river to less than 100 per ml. at the river mouth. The extremes of all of the counts obtained at high and at low tide at each station are plotted for the appropriate distance along the estuary in Figure 4.

The population of coliform bacteria expected at various locations as the result of dilution, dilution and mortality, and dilution, mortality and predation, are shown in Table IV, and are also plotted for comparison in Figure 4.

All of these calculations of expected populations depend upon the selection of the initial population size, which should be the population in the undiluted river water at New Brunswick. Five separate water samples at this location contained 96 per cent river water on the average, and gave counts of 110,000 cells per ml. It has been concluded from these observations that the population in the undiluted river water at the time of our survey was 115,000 cells per ml. At Perth Amboy the average population was 30 cells per ml. at high tide and 130 cells per ml. at low tide.

Dilution. The effect of dilution can be directly determined from the proportion of fresh water in each sample. On the

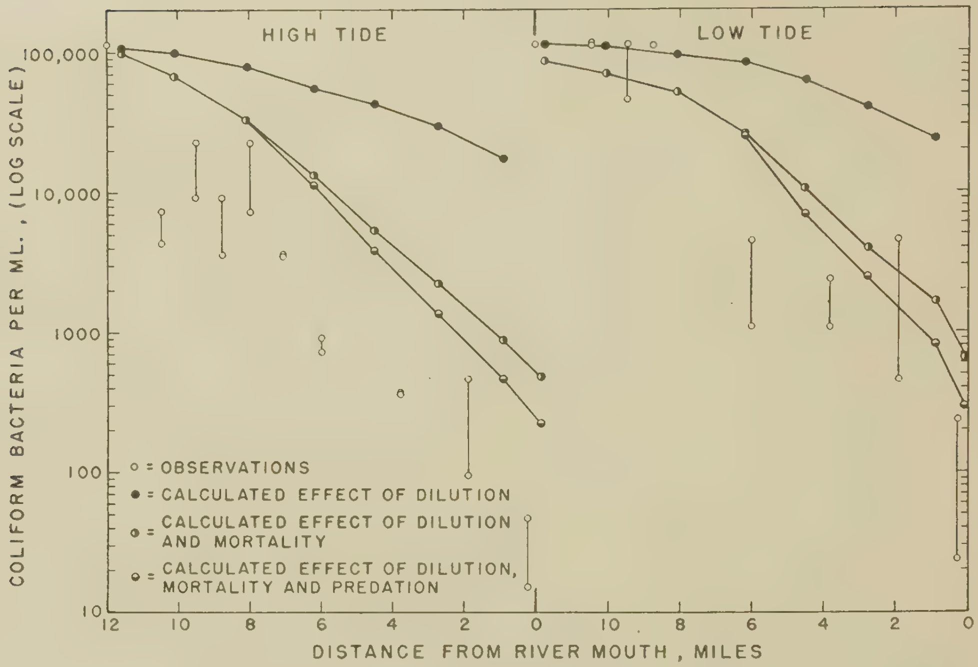

FIG. 4. The observed population of coliform bacteria in the Raritan River, and the populations expected as a result of dilution, of dilution and mortality, and of dilution, mortality and predation.

average, the water at New Brunswick (segment 2, 10.1 miles) was 85 per cent fresh at high tide, and 96 per cent fresh at low tide. At the mouth of the river the proportions were 14.5 per cent at high tide and 15 per cent at low tide. Through the course of the river, if dilution were the only process affecting the bacterial

TABLE IV. *Numbers of coliform bacteria expected in the various tidal excursion segments of the Raritan River*

Population expected (cells/ml.) as a result of:

Tide condition	Segment number	Average fraction fresh	Dilution	Dilution and mortality*	Dilution mortality* and predation
High	1	0.90	104,000	93,200	93,200
	2	0.85	98,000	68,000	68,000
	3	0.68	78,000	34,800	34,600
	4	0.49	56,400	13,600	11,200
	5	0.37	42,500	5,360	3,830
	6	0.26	30,000	2,230	1,360
	7	0.15	17,200	885	475
	8	0.145	16,700	472	214
Low	1	1.00	115,000	86,000	86,000
	2	0.96	110,000	70,000	70,000
	3	0.85	98,000	51,000	51,000
	4	0.73	84,000	26,100	26,000
	5	0.55	63,250	10,200	8,400
	6	0.35	40,200	4,000	2,900
	7	0.21	24,200	1,700	1,200
	8	0.15	17,200	655	350

[*] In this table and in Figure 4, mortality refers specifically to the computed effects of the bactericidal action of sea water.

numbers, the population should decrease proportionately, *i.e.,* to 16,700 at high tide and to 17,200 at low tide. It is obvious that dilution accounts for only a small part of the observed decrease, since these numbers are more than 100 times as great as the observed final populations.

Dilution and mortality. Two samples of surface water, collected at Stations 1 and 5, were analyzed for bactericidal activity by the methods previously described by Vaccaro *et al.* (1950). In both of these experiments the coefficient of death rate[2] was 1.15 days^{-1}, or 0.578 tides^{-1}. This coefficient has been used in calculating the effect of the bactericidal action of sea water.

The combined effects of dilution and the mortality due to the bactericidal action are sufficient to reduce the coliform population, as the water moves down the Raritan River, from an initial value of 115,000 per ml. to 472 per ml. at high tide, and to 655 per ml. at low tide. These two processes combined account for much of the decrease, since these numbers are only five to fifteen times as great as the observed final populations.

Dilution, mortality, and predation. It is also possible to make an approximate estimate of the importance of predation from the available data and published information. It should be emphasized, however, that this is undertaken merely to assess the relative importance of this process, and the results herein quoted are only first approximations. Fuller (1937) has studied the consumption of a small diatom *Nitzschia Closterium* by *Calanus finmarchicus* and found that the animals removed all of the diatoms in 0.2 ml. of water per hour. With two species of larger diatoms, the cells present in 3 to 8 ml. of water were consumed per hour (Harvey 1937). Thus it appears that calanoid zooplankton could be expected to filter living organisms from 12 to 192 ml. of water per day. With forms as small as the coliform bacteria it might be reasoned that the effective filtration would be closer to the lower value, though it is not actually known whether the zooplankton are able to remove bacteria from the water.

It should also be recognized that the species of zooplankton found in the Raritan River are not the same as those used in the above-quoted experiments.

In spite of these limitations it would appear to be advantageous to evaluate the possible effect of predation in determining the distribution of coliform bacteria. This has been done, making the assumption that the zooplankton organisms observed in the Raritan River might be expected to remove the bacteria contained in 20 ml. of water each day (10 ml. per tidal cycle).

The results of these calculations are also shown in Table IV and in Figure 4. In the upper end of the river there is no effective predation since no living zooplankton were collected in the tows obtained at these locations. By the time the circulation has brought the water to the mouth of the river the predation effect, as calculated, would decrease the bacterial population to about one-half of the population which would survive as a result of dilution and bactericidal action. This would give populations of 214 and 350 at high and low tides. These numbers are only 3 to 7 times as great as the observed final populations.

The observed decrease in the size of the population was from an initial concentration of 115,000 cells per ml. to final concentrations of 30 cells per ml. at high tide and 130 cells per ml. at low tide. The observed decreases are, therefore, 114,970 and 114,870 for high and low tides. The decreases which are expected as a result of the joint action of dilution, bactericidal action and predation are 114,786 and 114,650 at high and at low tides. These calculations thus account for more than 99 per cent of the observed decrease. The decreases are so large, however, that in spite of this agreement, the calculated populations at the mouth of the river are several times greater than the average observed populations.

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[2] In our previous work the coefficient of death rate has been calculated for base 10 logarithms. For the present purpose the coefficient is expressed in terms of base e logarithms, *i.e.,* 2.303 times the value of the coefficient as previously defined.

Discussion of Results

Rudolfs and Fletcher (1951) made an extensive survey of the pollution of Raritan River and Bay in 1950. Their average results indicate that the worst condition for the river was found just below New Brunswick, where the oxygen content approached zero and the mean coliform count was 62,000 per ml. At Victory Bridge (our station 2, Fig. 1) the dissolved oxygen saturation was increased to an average of 51.5 per cent and the mean coliform counts decreased to 440 per ml. Our observations are in substantial agreement with the results of Rudolfs' and Fletcher's extensive survey. They comment on the considerable change which has occurred in the river since the survey made by Rudolfs and Heukelekian (1942).

The calculations presented indicate that the joint effects of dilution, bactericidal action of sea water and predation by zooplankton are sufficient to account for practically all of the disappearance of coliform bacteria throughout a ten-mile length of the Raritan River. The effects of the three processes are cumulative factorially, and the relative effectiveness of each process can be conveniently expressed by the ratio of the computed populations in each segment (Table V). The effect of dilution, which acts on all materials in the water equally, is assigned a relative effectiveness of unity. When the population expected as a result of dilution is divided by that expected as the cumulative result of dilution and bactericidal action, the relative effectiveness of the latter process is obtained. When the population expected as a result of both dilution and bactericidal action is, in turn, divided by that expected as a result of predation in addition to these two processes, the relative effectiveness of predation is obtained.

In the river end of the estuary the effect of the bactericidal process is not very much greater than that of dilution. As the water moves down the estuary the increasing time greatly increases the effectiveness of the bactericidal action until, at the mouth of the river at high tide, this process has accounted for thirty-five times as much disappearance as has dilution. At low tide, when the water at the mouth of the estuary has not been within the estuary for so long a period of time, the effect of this mortality is twenty-six times as great as that of dilution. Similarly, the effect of predation increases as one moves down the estuary until it is ultimately twice as great as the dilution effect. The residual disappearance of bacteria which is not accounted for by the three processes considered would, at the river mouth, indicate that the unevaluated processes are more important than dilution or predation, but much less important than the bactericidal action of sea water. The observed average population of 30 and 130 cells per ml. at high and low tides, would indicate that the relative effectiveness of unevaluated processes was 7 to 3 times as important as dilution.

Table V. *The relative effectiveness of dilution, bactericidal action, and predation in decreasing the coliform bacteria in the Raritan River*

Tide condition	Segment	Dilution	Bactericidal action	Predation
High	1	1.00	1.12	1.00
	2	1.00	1.44	1.00
	3	1.00	2.24	1.00
	4	1.00	4.15	1.21
	5	1.00	7.94	1.40
	6	1.00	13.4	1.64
	7	1.00	19.4	1.86
	8	1.00	35.4	2.20
Low	1	1.00	1.34	1.00
	2	1.00	1.57	1.00
	3	1.00	1.92	1.00
	4	1.00	3.21	1.00
	5	1.00	6.20	1.21
	6	1.00	10.0	1.38
	7	1.00	14.2	1.67
	8	1.00	26.3	1.82

It is of interest to speculate concerning the unevaluated disappearance of coliform bacteria. Sedimentation and the resultant accumulation of the bacteria on the bottom could be expected to have a significant effect on the population in the water. Weiss (1951) has shown that when silts are centrifuged from river waters as much as 50 per cent of an *E. coli* population may also be removed. When mixtures of sea water and river water were used the removal of *E. coli* was less effective. Our survey did not provide the data necessary to evaluate the effect of sedimentation, but it seems probable that this process could account for much or all of the residual disappearance of bacteria within the river.

It is also possible that the coefficients of mortality and of predation used in these calculations are lower than those actually obtaining in the river at the time of our survey. Vaccaro *et al.* (1950) observed coefficients of mortality as great as 2.88 days^{-1}, a value more than twice as great as the one observed on Raritan River water. The population expected at high tide at the mouth of the river using this coefficient of mortality would be 91, or less than one-fifth of the population predicted in Table IV. If one were to assume that the predation effect was the maximum observed, namely that the zooplankton would filter 100 ml. of water per tidal cycle instead of 10, as used above, a further decrease to 36 cells per ml. would be expected. This concentration is virtually identical with the average value of 30 cells per ml. observed at this location at high tide. The coefficients used in the calculations were selected as the most probable values, but it is clear that coefficients within the possible limits could be chosen so that the calculations would fit the observations more precisely.

SUMMARY

1. The distributions of salinity, oxygen and bacteria in the Raritan River are described.

2. A method is presented for evaluating the relative effects of dilution, the bactericidal action of sea water and of predation in reducing the population of coliform bacteria in a tidal estuary.

3. It is shown that these three processes account for more than 99 per cent of the decrease in coliform bacteria in the Raritan River. The bactericidal action is the most important process, followed by predation and dilution.

4. Unevaluated processes contributing to the decrease are more important than dilution or predation but much less important than the bactericidal action.

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Contribution No. 562

RECENT FINDINGS ABOUT THE DEEP SCATTERING LAYER[1]

By

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ABSTRACT

Sound scattering observations in deep water are reported for the frequency range from 2 to 20 kc. An explosive sound source was employed to give a sound having high acoustic pressures throughout the frequency range. The receiver was directed vertically downward in the water; the recorder allowed simultaneous recording over several frequency bands. Scattering showed marked peaking as a function of both depth and frequency down to 5 kc, but not below, so far as the observations extend. Peaked scattering at all frequencies exhibits diurnal migration; thus there is continued indication that marine animals are the principal scatterers throughout the frequency range studied. The peaking as a function of frequency above 5 kc suggests that common and abundant animals in deep water do not greatly exceed linear dimensions of the order of 30 cm. The marked differences observed in the frequency and depth dependence of scattering from place to place, compared with their reproducibility over a limited area and time, suggest that the frequency dependence of scattering may eventually be employed for limited identification of the animals.

INTRODUCTION

The occurrence of stratification of sound scattering, first discovered in the Pacific Ocean [(2), (3), (4), (5) and (6)], has been found to be nearly world-wide, and such characteristics as the correlation between layer depth and altitude of the sun have been studied [(8), (9) and (10)]. The hypothesis by Johnson (4) that the scatterers are marine

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animals is widely accepted, but there is no general agreement about their identity. Several animal groups have been proposed: Hersey and Moore (9) suggested euphausid shrimp, Lyman (10) proposed squid, and Chapman (7) suggested that fish are responsible. A recent discussion by Marshall (11) reviews previous analyses and suggests that certain bathypelagic fishes with swim bladders have appropriate distribution and habits to account for some of the scattering. Definite identification will depend on some direct means such as net towing or underwater photography. However, acoustic observations are of value in approximating the size and distribution of the scatterers. The present paper describes an approach to this end by investigating their frequency dependent characteristics.

The acoustic record, plotted as a function of time, presents the combined echo level from all scatterers in a volume of water determined by the time after the emission of the sound signal and its own duration. Standard methods (2) for analyzing the scattering record give, as a function of distance from the sound source, the average fraction of sound energy scattered per cubic meter of water. This may be regarded as the total scattering cross section that "intercepts" the sound beam per cubic meter; it is dependent on the population density of scatterers, their size distribution, their acoustical properties, and the frequency of the sound signal.

The scattering cross section of an individual, in general not equal to the physical cross section it presents to the sound beam, depends on its physical size in relation to the wave length of the sound beam and on its own acoustical properties. Hence no acoustical measurement of cross section will yield the physical size distribution directly. Raitt (15) has observed the distribution of the acoustical cross section of individual scatterers by measuring the amplitude of many individual echoes from very short pulses of sound.

The detailed scattering properties of marine animals are expected to be complicated, and it is unlikely that theoretical expressions for their scattering can be derived by any practical effort. However, it is reasonable to expect that the effects of shape and size will turn out to be sufficiently similar to those of simpler forms of scatterers to permit some conclusions to be drawn about the size distribution from frequency dependence. In the usual treatment of the scattering problem, three regions of approximation, in which rather different types of frequency dependence hold, are useful from a practical standpoint:

I. The scatterer is much smaller than the wave length of sound,
II. The scatterer is comparable to the wave length, and
III. The scatterer is much larger than the wave length.

In I, Rayleigh [(16) vol. II, paragraph 296] has shown that the acoustic pressure of the scattered wave is proportional to the square of the frequency and to the volume of the scatterer regardless of its shape. Hence for wave lengths long compared with the scatterer, scattering should increase rapidly with frequency. In II, the scattering in any given direction may fluctuate considerably with frequency, depending on the acoustical properties of the scatterer compared with the medium. The general nature of results to be anticipated in marine scattering was outlined by Anderson (1), who computed in detail the back scattering from fluid spheres; he considered this to be a reasonable starting point for the study of marine animal scattering. In III, scattering is independent of frequency and depends only on the acoustical properties of the scatterer and the cross section it presents to the sound beam.

Since marine animals vary in size from a fraction of a centimeter to a few meters, it is apparent that they may occupy in turn any of the three regions of approximation discussed above for the ordinary sonic and lower ultrasonic frequencies. A study (3) has been made in which scattering at 10, 20, 40 and 80 kc was observed in rapid succession to investigate frequency dependence in the deep scattering layer. The results indicated that the scattering does not follow the Rayleigh law. By extending sonic observations to lower frequencies it should be possible to find the region where the wave length is much larger than the largest abundant scatterers and hence determine where scattering falls off sharply as the frequency is decreased. The present paper describes an investigation in which scattering was recorded down to 2 kc in an attempt to do this by means of a technique which allowed simultaneous recording of several frequency bands.

OBSERVATIONS

The first observations were made in the vicinity of Lat. 38° 30′ N Long. 71° W on cruises of the R/V Caryn from 2 to 11 August 1949 and of the R/V Atlantis from 22 to 30 September 1949. A third cruise, on the R/V Atlantis between January and April 1950, covered a considerable area between Cape Cod and the Antilles.

The sound source employed was a ½ lb. block of TNT which was detonated at a depth of about ½ m and 30 to 50 m from the receiver. The receiver was a somewhat directional rochelle salt transducer towed at shallow depth astern of the observing ship on the first cruise; subsequently it was mounted in the keel. In both cases the transducer was directed vertically downward. Sounds received by the transducer were filtered by band-pass filters in the separate channels of a multichannel amplifier, rectified, and then fed to galvanometers to be recorded photographically. Fig. 1 shows representative records. Here four channels were employed and three were recorded at two dynamic levels, roughly 20 db apart, thereby allowing both loud and faint sounds to be recorded on the same record. Timing markers, vertical lines 1/100 seconds apart, were recorded by a suitably controlled interrupter with every tenth line accentuated to facilitate scaling. Depth in meters and the corresponding travel times are indicated below the record. The explosion provides an intense source of sound at all frequencies, and the filtered amplifiers provide a means of recording scattering from the explosion in various frequency bands. The receiver, directed vertically downward, discriminates against sound scattered from surface waves or from scatterers in the water at wide angles from the vertical.

Fig. 2 is a series of records from the CARYN cruise in which various frequency bands from 19.6 to 2 kc were employed. The 19.6 kc filter was used throughout the series for comparison. The change in character from one band to another is apparent from an inspection of the records. Observe that there is a peak of scattering at about 140 m on the 15 and 19.6 kc traces which does not appear at any of the low frequencies. Similarly, the very prominent scattering at 400 to 500 m at 15 and 19.6 kc is reproduced at 10 kc but at no lower frequency. At 8 kc a peak of different shape and of slightly different depth is recorded. At 5 kc a much broader and deeper peak is recorded, while at 2 kc there is no evidence of peaking. The very sharp character of the peak at 400 to 500 m on the 19.6 kc trace is found consistently only in certain localities in the Atlantic; it is best known just north of the Gulf Stream where this series was recorded. Fig. 1 shows a more usual recording in which the deep scattering layer (i. e., on the 15 kc trace) is broader and more diffuse; this record was also made north of the Gulf Stream but at a different location.

A General Radio Sound Analyzer (Type 760A) was used to examine in detail the peak at 5 kc. Fig. 1 shows three records in which the Analyzer was employed as a filter at 3, 5.5, and 7.5 kc. In the first (3 kc) the scattered return is relatively low in amplitude compared with the second (5.5 kc), while the third (7.5 kc) is of lower amplitude and is somewhat different in character, since the shallower peak begins to appear here. We had no means of examining in such detail the transition from one frequency band to another above 7.5 kc.

Several sequences of records taken at 5 and 10 minute intervals were made through both sunrise and sunset. Although there are striking individual differences in the various sets of observations, all show marked evidence of vertical migration of some of the scatterers at all frequencies. This is illustrated by Fig. 3, showing selected records taken from a series from 1410 to 1850 on March 4, 1950 at Lat. 29° 00′ N, Long. 62° 05′ W. (The time of local sunset was 1815.) All four records were taken at the same gain settings of the analyzer, and relative amplitudes on the same frequency trace from record to record at a given depth may be compared as a rough measure of the concentration of scatterers there. The record at 1410 is a typical mid-day record for this region. The scattering from 0 to about 75 m on the 20 and 15 kc traces and from 0 to about 150 m at the lower frequencies is probably a combination of scattering from surface waves and scatterers in the water. In many instances, peaks of scattering are reproducible at shallower depths, but generally the record is not usable for about 0.1 sec. after the shock wave (i. e., 75 m). On the 20 kc trace a somewhat complicated layer extends from about 250 to 290 m. At greater depths no scattered return is above the general background level on the sensitive trace. On the 1627 record this layer is not evident, the scattering being diffuse and of low amplitude at depths greater than about 110 m. On the 1805 and 1850 records, however, marked stratification is found from about 75 to 180 m where none was previously evident. On the 15 kc traces a somewhat more striking migration is seen where a mid-day layer extending from 380 to 650 m apparently split by 1627, the shallower portion migrating to a very shallow depth by 1805 (55 to 220 m); meanwhile the deeper portion, though still identifiable as a layer at about its mid-day depth throughout the series, apparently weakens in concentration between 1805 and 1850 to a small fraction of its mid-day amplitude. At 10, 8, and 5 kc the scattering is diffusely distributed in depth to slightly deeper than 1000 m. Hence the migration is not evident progressively through these records. However, an increase in the scattering amplitude at the shallower depths is evident at all three frequencies between 1805 and 1850, which coincides with a general decrease in the scattering amplitude at depth. These records were selected from a more detailed sequence which demonstrates that the changes described took place in a gradual manner throughout the period covered.

DISCUSSION

The examples of scattering records in Figs. 1, 2 and 3 are not representative of all of the variations that have been observed amongst the 200-odd records which have now been taken in the western North Atlantic, but they may be taken as typical. The records of each figure, taken within a few miles of one another, are reproducible, in general character at least. However, the locations for the three figures differ, and there is correspondingly considerable variation from one figure to another, not only in the character of the depth dependence at any one frequency but also in even the most general aspects of the frequency dependence. For example, in the case of Fig. 2, the 10 kc record is very similar to those at 15 and 19.6 kc but different from those at 8 and 5 kc, whereas in Fig. 1 the 10 kc trace is strikingly different from all frequencies but 7.5 kc. Again in Fig. 3 the 10, 8, and 5 kc traces are all rather similar. Other individual features, such as the peak in Fig. 2 at 70 m depth on the 15 and 19.6 kc traces, which do not appear at the lower frequencies, have proven to be reproducible in local areas that may be miles in extent. Diurnal migration, which is observed at all frequencies for which there are scattering peaks, is strong evidence that marine animals are the principal scatterers. Hence, observations of this type provide a means of following the migration and of determining the extent and concentration of different groups of marine animals, discriminated from one another by means of frequency dependence.

All records obtained thus far show some evidence of variation of scattering with both depth and frequency. No pronounced peaking as a function of frequency has been observed below 5 kc. This suggests that no heavy concentrations of animals larger than 30 cm, the wave length at 5 kc, have been encountered during the observations and hence are not commonly found in the western North Atlantic. However, since the frequency region below 2 kc has not been investigated extensively, and since we know little in detail of the exact manner in which marine animals scatter sound, it is premature to conclude that this is necessarily so. Further, for the latter reason we cannot now predict the detail with which it may be possible to interpret the sound scattering through the region of peaking. However, it seems possible that the scattering variation with frequency may tell enough about the physical size of the scatterers to allow some limited identification of kinds of animals, particularly if the mode of taking the scattering observations allows the determination of other characteristics such as schooling habits, movement of groups or individuals, or other features that would aid identification.

Much of the justification for such a prediction must rest on a satisfactory demonstration that the supposed scatterers are present and are capable of scattering sound as observed. In the series of observations discussed here, net tows at different depths were made only on the August 1949 cruise of the R/V CARYN. These were made with a pair of ¾ m stramen nets towed at speeds from 1.5 to 2 knots.

The biologist making the collections aptly remarked that such an operation would catch only "the maimed, the halt and the blind." However, daytime hauls below 250 m did catch appreciable numbers of animals whose lengths were comparable with the wave length over much of the frequency range observed. The question whether planktonic forms have adequate scattering cross sections to account for observed scattering coefficients is not completely answered. Nevertheless, a good indication that they do comes from unpublished measurements of scattering from small inshore shrimp made by Mr. P. F. Smith at Woods Hole. At frequencies between 20 and 30 kc he found that shrimp [*Palaemonetes vulgaris* (Say)], roughly 2.5 to 3.5 cm long, had quite adequate scattering power to account for the scattering coefficients observed for the peak of the scattering layer given in the University of California work (2), assuming concentrations of the order of 20 shrimp per cubic meter. Thus it seems reasonable to suppose that planktonic crustaceans of various sizes may be capable of scattering sound over a considerable frequency range with sufficient power to account for much of the observed scattering. Of course, this does not preclude the possibility that other types of animals, not necessarily all planktonic, can scatter sound sufficiently to be observed in the scattering layers of the deep ocean.

CONCLUDING REMARKS

1. Peaks of sound scattering as a function of frequency occur in the deep ocean for frequencies at and above 5 kc, suggesting, by analogy to the scattering properties of simple geometrical forms, that the physical size of the common abundant scatterers is comparable to the wave length above that frequency, i. e., wave lengths less than 30 cm.
2. Observations of diurnal migration at all frequencies where peaking occurs is a strong indication that the scatterers are zooplankton. Other measurements indicate that planktonic crustaceans or other associated organisms such as fish probably have adequate scattering power to account for the observed scattering.
3. Sound scattering as a function of both depth and frequency is reproducible, in general outline at least, over limited areas, but it varies considerably over the part of the ocean studied. This suggests that concentrations of different animals characteristic of a given general locality control the observed scattering, thus providing a limited means of identifying them.

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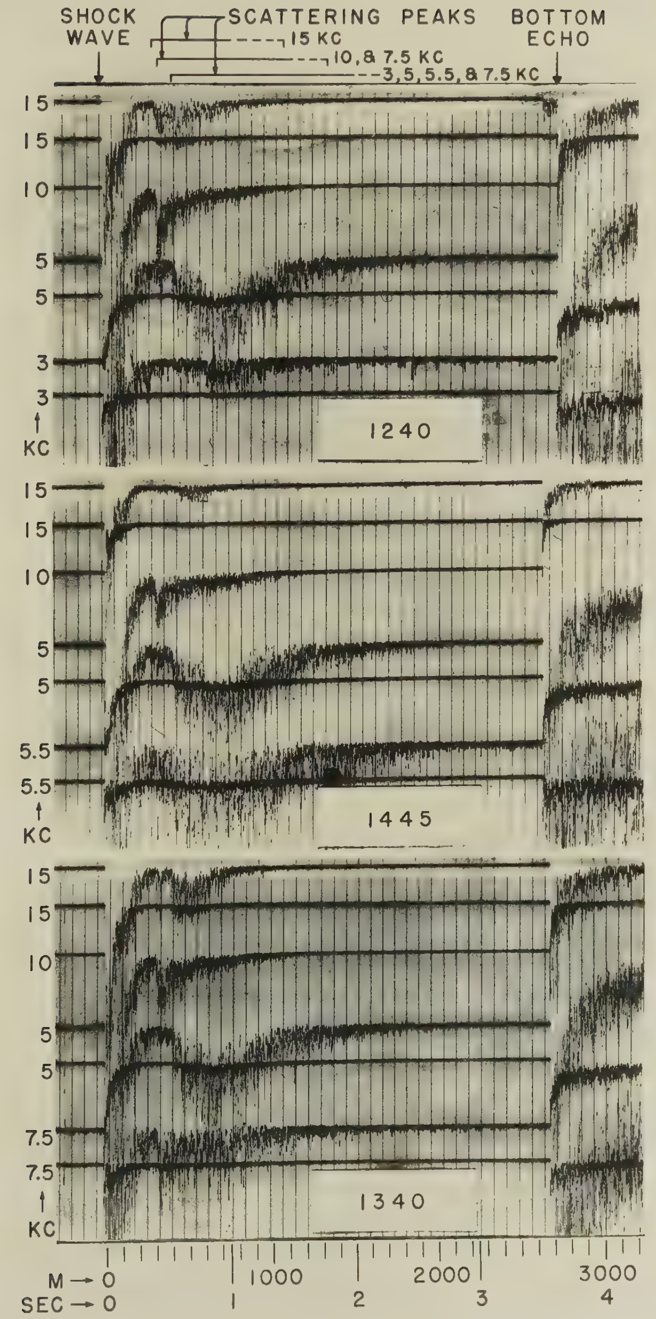

Figure 1. Representative scattering records.

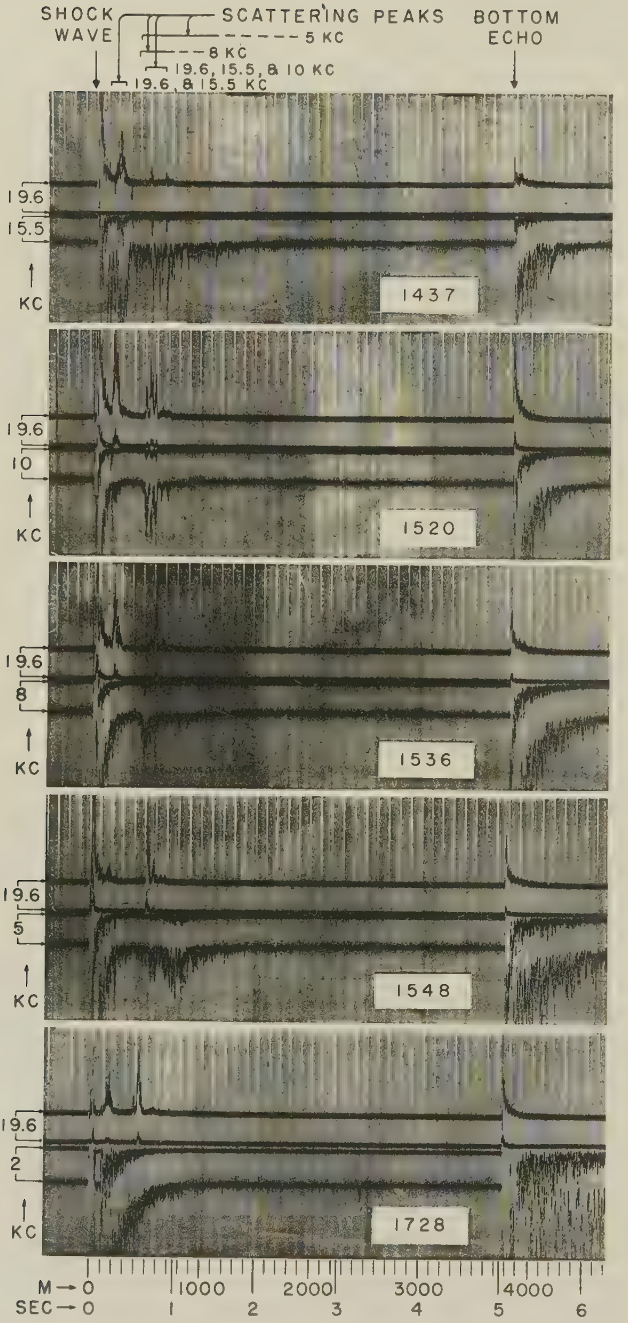

Figure 2. Sound scattering at various frequencies at Lat. 38°30'N, 71°55'W.

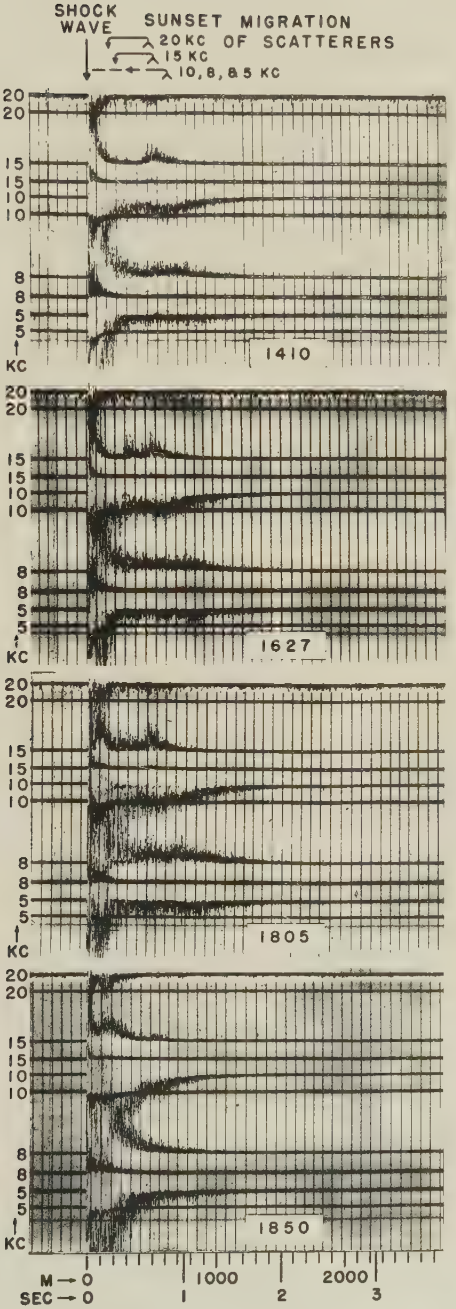

Figure 3. Sunset scattering record sequence.

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Contribution No. 563

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ATMOSPHERIC SALT PARTICLES AND RAINDROPS

By Alfred H. Woodcock

ATMOSPHERIC SALT PARTICLES AND RAINDROPS

By Alfred H. Woodcock

Woods Hole Oceanographic Institution[1]

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ABSTRACT

Marshall and Palmer (1948) have shown that, for rains of a given intensity, there is a definite distribution curve of number of raindrops of a particular range of diameter. The writer has indicated here that the chlorinity of rains also varies with rain intensity. Recently obtained data, concerning atmospheric sea salt, are presented in the form of distribution curves. These curves show the number of sea-salt particles sampled at different altitudes, of a given weight range, plotted against the weight. A computation is made, using a salt-particle distribution curve obtained at cloud levels, in which water is added to each particle until it reaches an assumed chlorinity for a given rain intensity. Each particle is thereby increased in size and becomes a drop of a new weight. The distribution curves of these computed drops are compared to the observed distribution curves of Marshall and Palmer, for various rain intensities, and are found to be remarkably similar. This result implies that, in the process of growth, the droplets containing each salt particle grow to raindrop size through coalescence with much more numerous and relatively non-saline cloud droplets.

The numbers of droplets in cumulus clouds over the sea are compared to the numbers of condensation nuclei in the sub-cloud layer and to the number of larger sea-salt particles.

A method of sampling the large sparsely-distributed salt particles in the atmosphere is described briefly.

1. Introduction

The presence of variable quantities of sea salts in cloud, fog and rain waters is well known (Köhler, 1936; Houghton and Radford, 1938; Takeuchi, 1949; *etc.*) and has led to much discussion of the role of sea-salt particles in rain formation (Simpson, 1941a; Wright, 1940; Köhler, 1941; Findeisen, 1937). Crystalline particles have been sampled in relatively clear marine air at low altitudes by Owens (1926). In clear marine air at cloud levels, Woodcock and Gifford (1949) have sampled salt particles which have a wide range of weights. Thus, salts are found in precipitation elements and also in the relatively clear air in which these elements develop.

Little discussion has been found in the meteorological literature about possible relationships between the number and weight of salt particles in the clear air and the salt in cloud and raindrops. The present paper indicates that a relationship exists between the distribution of weight of salt particles in clear air and the distribution of size of raindrops of varying salt content.

The primary purpose of this paper is to show that large particles of sea salt are present at cloud levels in marine air, and to give evidence that these particles take part in the formation of rain. In this study, three kinds of observational data are used:

1. The weights and numbers of the larger sea-salt particles sampled in the lower atmosphere over the sea and over the land.
2. The chloride content of waters from rains of varying intensity.
3. The size and number of drops in rains of varying intensity.

TABLE 1. Multi-slide data from air-salt samples taken on a pier at Woods Hole, Mass., 1140 to 1711 EST 15 September 1950. Wind: SW. Visibility: 3 mi. Clouds: cu, 5/10. T: 18.7 to 19.0C; T_w: 18.0 to 18.1C. Sampling height: 5 m above sea surface.

	Sampling strip widths (mm)						
	1	3	10	30	100	1 (Ag rods)	3
1. Sampling method used	impact	impact	impact	impact	impact	impact	precipitation
2. Slide-exposure duration (sec)	52 (av.)	513	3,750	11,700	18,850	18,850	15,200
3. Average wind speed (m/sec)	9.6	9.1	9.1	8.8	8.9	9.1	9.8
4. Slide-exposure length (m)	500	5000	34,100	103,000	133,400	171,500	—
5. Sea salt cm^{-3} of air ($\mu\mu$g)			8.87			9.21	8.64
6. Number of salt particles cm^{-3} of air			0.35			—	0.66
7. Covering fraction*	.062	.035	.069	.078	.020	—	.0003
8. Number of particles measured			2002			—	1240
9. Method used to measure salt wt.			isopiestic			titration	isopiestic

* See footnote, table 2.

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For present purposes, data from category 3 have been taken from the literature. Concerning classes 1 and 2, the observational data available in the literature are inadequate. Hence, new observations of the larger salt particles in the air and of the chloride in rain waters were made and are presented below. The observations of the larger salt particles were made by use of a simple modification of sampling methods already described by Woodcock and Gifford (1949). This modified technique is described at the end of this paper. A standard method was used to determine the chlorides in rain waters. The silver nitrate required to precipitate the chlorides was measured by micro-burette.

2. Vertical distribution of salt particles over the sea

Fig. 1 shows the distribution of sea-salt particles sampled at the end of a dock in Woods Hole, Mass. Table 1 gives other sampling conditions. Previously the largest and most sparsely distributed particles commonly sampled in marine air weighed about 10^{-9} g (= $10^{3} \mu\mu g$) and were present in numbers of about four m^{-3} of air $\mu\mu g^{-1}$ range in weight. In fig. 1 it can be seen, however, that the new sampling technique extends this limit to about 10^{-4} particles $m^{-3} \mu\mu g^{-1}$ range, at a weight of about $3 \times 10^{4} \mu\mu g$. Questions arose concerning the distribution of these larger nuclei in marine atmospheres at cloud levels.

The distribution of the weight and number of salt nuclei at various altitudes over the sea east of Miami, Fla., is shown on figs. 2 and 3, and tables 2 and 3 show other relevant data. Winds were easterly at all sampling levels. These data show again the very similar distribution of nuclei weight and number at different heights within the sub-cloud layer (see also Woodcock and Gifford, 1949, fig. 15). In addition, the data show that the larger nuclei present near the sea surface are also carried up to cloud levels.

In considering the significance of these large salt

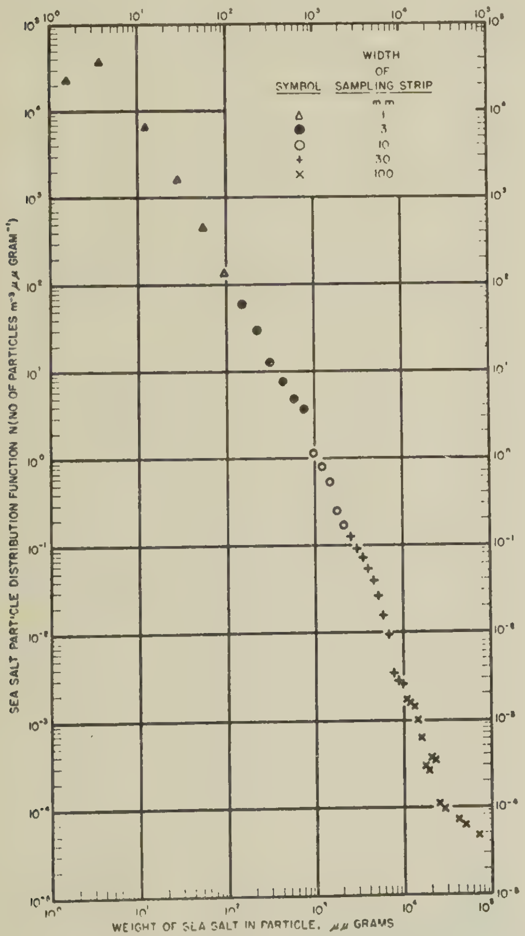

Fig. 1. Corrected distribution of sea-salt particles among samples taken 15 September 1950, 5 m above sea surface. Symbols indicate widths of strips used to sample various particle sizes. See table 1 and text for further discussion.

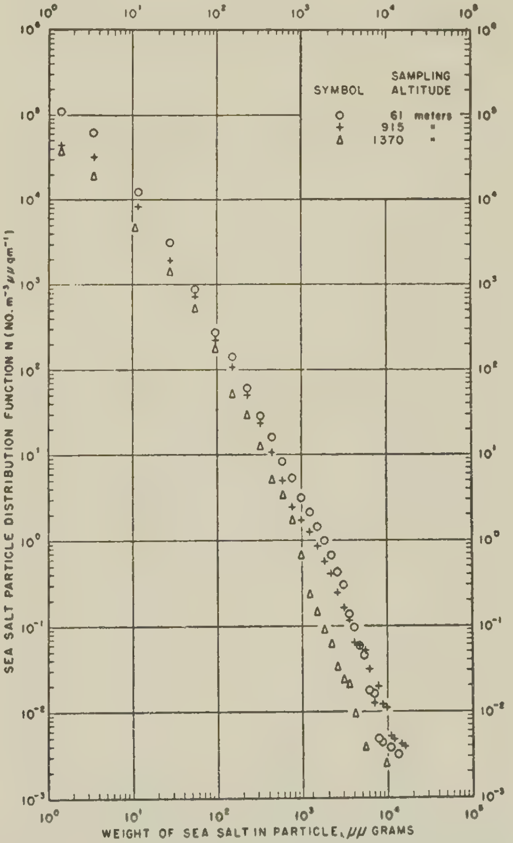

Fig. 2. Corrected sea-salt particle distribution among samples taken in lower atmosphere over sea on 8 November 1950. See table 2 and text for further information.

particles in the formation of rain over land, it is necessary to show that they are present at cloud levels at considerable distances from the sea.

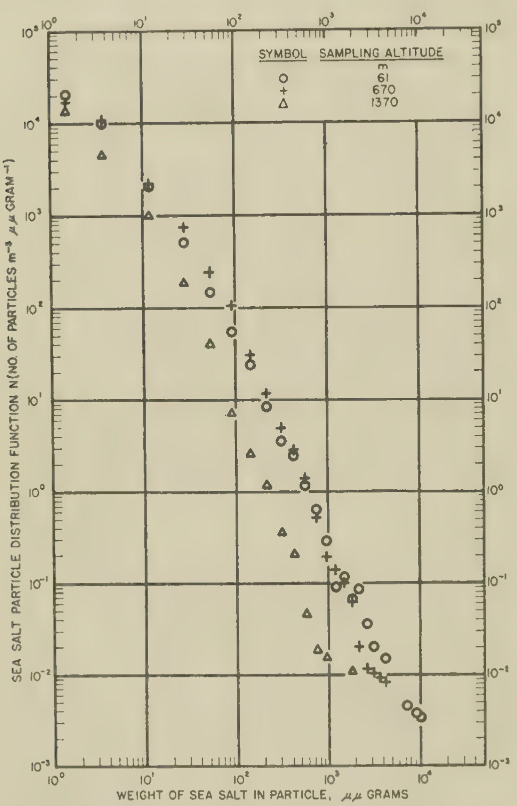

FIG. 3. Corrected distribution of sea-salt particles among samples taken in lower atmosphere over sea on 14 November 1950. For further information, see table 3 and text.

TABLE 2. Data concerning air-salt samples taken over the sea from an airplane near Miami, Fla., 8 November 1950 (lat. 25°51′N, long. 80°00′W). Surface wind: ENE, force 3. Sampling speed: 26.8 m/sec. Scattered cu clouds, bases at 1000 m. Rain showers visible over sea.

	Height (m)		
	61	915	1370
1. Time (EST)	1135	1310	1425
2. Pressure (mb)	1010.5	913	864
3. T (deg C)	24.2	15.9	12.4
4. T_w (deg C)	18.9	14.1	10.0
5. RH (per cent)	61	82	75
6. Sea salt in air ($\mu\mu g/cm^3$)	19.3	13.5	6.1
7. Number salt particles cm^3	0.94	0.49	0.34
8. Average covering fraction*	.011	.047	.020
9. No. of particles measured	775	777	694

* The covering fraction (Langmuir, 1944) equals a/a_r, where a = area covered by hemispheric droplets on slides, and a_r = total area over which droplet counts were made. Langmuir has indicated that this ratio should not exceed about 0.1. [It should be noted that Woodcock and Gifford (1949) have incorrectly referred to the covering fraction as "per cent of slide surface covered" (p. 189), though the actual values they give are the correct ratios.]

3. Vertical distribution of salt particles over the land

The distribution of salt particles sampled near the town of Everglades, Fla., is given in fig. 4, and table 4 gives other sampling data. The air at all sampling levels at this location had flowed from an easterly

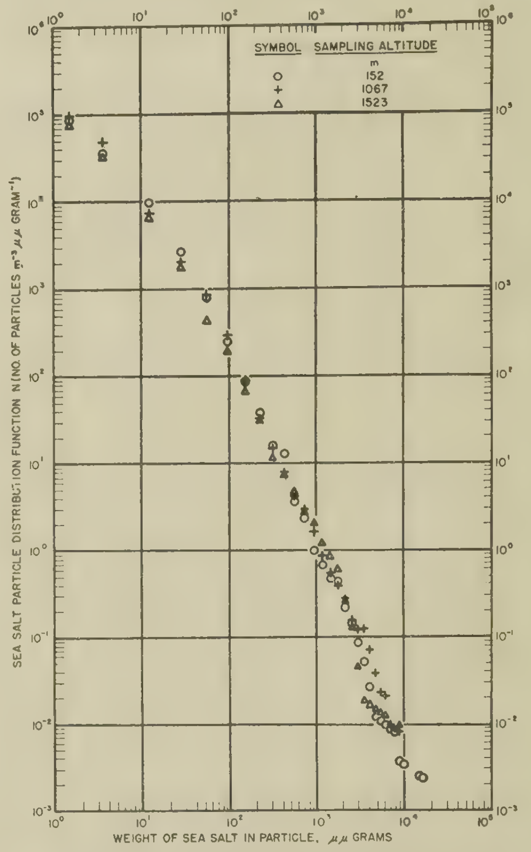

FIG. 4. Corrected distribution of sea-salt particles among samples taken in marine air after passage over about 110 km of land, 16 November 1950. For further information, see table 4 and text.

TABLE 3. Data concerning air-salt samples taken over the sea from an airplane near Miami, Fla., 14 November 1950 (lat. 25°51′N, long. 80°00′W). Surface wind: ENE, force 3 to 4. Scattered cu clouds, bases about 750 m. No rain showers visible during flight. Sampling speed: 26.8 m/sec.

	Height (m)		
	61	670	1370
1. Time (EST)	1055	1200	1316
2. Pressure (mb)	1016.5	946	870
3. T (deg C)	24.1	18.3	13.6
4. T_w (deg C)	19.8	16.6	10.7
5. RH (per cent)	67	85	71
6. Sea salt in air ($\mu\mu g/cm^3$)	2.7	3.4	0.6
7. Number salt particles cm^{-3}	.44	.25	.08
8. Average covering fraction	.002	.008	.0004
9. No. of particles measured	602	493	433

TABLE 4. Data concerning air-salt samples taken over the land from an airplane near Everglades, Fla., 16 November 1950 (lat. 25°53′N, long. 81°21′W). Surface wind: E, 10 mi/hr. Scattered cu clouds, bases about 1150 m. Rain showers visible. Sampling speed: 26.8 m/sec.

	Height (m)		
	152	1067	1523
1. Time (EST)	1425	1530	1636
2. Pressure (mb)	1004.5	900	852
3. T (deg C)	24.3	15.3	11.6
4. T_w (deg C)	18.0	13.9	10.0
5. RH (per cent)	54	86	82
6. Sea salt in air ($\mu\mu g/cm^3$)	11.9	12.3	9.7
7. Number salt particles cm $^{-3}$	.694	.750	.557
8. Average covering fraction	<.008	<.04	<.03
9. No. of particles measured	716	715	734

direction and had traveled over about 110 km of land since crossing the Florida east coast. Passage over land seems to have thoroughly mixed the particles in the sub-cloud and cloud layers, presumably due to increased atmospheric turbulence. The cloud layer over the open sea usually contains fewer particles than the sub-cloud layer (for example, see fig. 2). Fig. 4 also shows that marine air, after flowing over many miles of land, still contains many large sea-salt particles. No evidence of other hygroscopic nuclei was found on the sampling slides exposed over land.

The presence of these large salt particles at cloud levels over land raised the question of their possible role in the processes of rain formation. This question is discussed below, and it is found that the weights and numbers of these particles, when related to the size and chlorinity of raindrops, are appropriate to and support the assumption that each salt particle becomes a raindrop.

4. Sizes of salt particles as droplets at high relative humidities

The approximate range of weights of the salt particles which have been sampled at cloud levels is shown in the first column of table 5. Column 2 shows the radii of these particles when assumed to be crystalline spheres, and columns 3 to 9 show their radii as liquid spheres having various concentrations of water and sea salt. The increases in radius shown in columns 3, 4 and 5 are observed to occur among atmospheric salt particles measured in the laboratory and are shown in major part by Woodcock and Gifford (figs. 4 and 8, 1949). It is assumed that similar changes in radius would occur with relative-humidity changes in the free air. Columns 6 through 10 give computed radii at decreasing concentrations, which have been measured in fog, cloud and rain waters.[2] Equation (2), below, was used in deriving the drop sizes given.

It is interesting that, within the usual range of salt concentration of rain waters, columns 7 through 10, all the particles become drops having a range of size comparable to that of raindrops (*i.e.*, radius about 150 to 3000μ, as shown in column 10). Expressing this in another way, the evaporation of raindrops having the usual range of salt concentration and size would result in a residue of individual salt particles having a weight range which falls within that actually observed among salt particles found in the air at cloud levels. Column 5 shows that, at the concentration and relative humidity presumed to exist as salt-laden air enters a cumulus cloud, the larger particles have already attained a size ample for growth by accretion[3] (see Langmuir, 1948, table 5, for critical drop-sizes at which accretion can occur).

Thus, table 5 gives evidence that the distribution of weight of the larger salt particles at cloud levels would favor their growth by accretion shortly after entering a cloud (this has been recently discussed by Ludlam, 1951). The table also lends support to the idea that individual salt particles become raindrops, since the distribution of weight among the particles is just appropriate for the formation of drops having rain-

TABLE 5. Radii (microns) of sea-salt particles as crystalline spheres (column 2) and liquid spheres at the concentrations found with increasing relative humidity and at the concentrations found in fog, cloud and rain waters.

Weight of sea salt in nucleus	Salt-particle radius (μ) at various concentrations of sea salt and water*								
1	2	3	4	5	6	7	8	9	10
$\mu\mu g$	Crystalline spheres** RH <50%	17.9×10^4 mg/l RH: 90%	35.9×10^3 mg/l RH: 98%	17.8×10^3 mg/l RH: 99%	5×10^2 mg/l	10^2 mg/l	10 mg/l	1 mg/l	10^{-1} mg/l
1	0.5	1.1	1.88	2.4	7.8	13.4	28.8	61.9	134
10	1.0	2.5	4.05	5.1	16.8	28.8	61.9	134	288
10^2	2.2	5.1	8.7	11.0	36.2	61.9	134	288	619
10^3	4.8	11.0	18.8	23.7	78	134	288	619	1340
10^4	10.3	24.7	40.5	51.1	168	288	619	1340	2880
10^5	22.1	51.0	87.2	110	362	619	1340	2880	—

* The radius of some of the smaller droplets will actually be somewhat less, due to curvature effects upon vapor pressure. This fact does not, however, affect the present use of this table.

** Density about 2.2.

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[2] Salt in cloud, fog, and rain waters is usually expressed as weight of Cl. For convenience, these Cl values are, in this paper, converted to weight of sea salt by multiplying by 1.8, the ratio of total salts to Cl in sea water. Miyake (1948) has indicated that this ratio may be too low among salts in precipitation waters, but his results need not be considered here.

[3] Measurements of sea-salt particles suspended on spider webs have shown that a droplet formed on a particle weighing about 10,000$\mu\mu g$ will grow to 70 per cent of the equilibrium size (40-μ radius) in about 200 sec, and 80 per cent of equilibrium size in 900 sec, when the relative humidity is rapidly changed from 70 to 98 per cent. These measurements, which were made in the laboratory, are to be extended and will be published later.

drop dimensions when their salt concentration is equal to the salt concentrations found in rain waters. This would mean, of course, that the process of growth of the salt particles to raindrop size would require the addition of relatively pure water. This point will be discussed later.

It has been shown that the weight of the salt particles found at cloud levels is appropriate to the assumption that individual salt particles are the nuclei upon which raindrops form. As indicated in the next section, the number as well as the weight of the salt particles in the air is appropriate and lends support to the idea that the individual particles become raindrops.

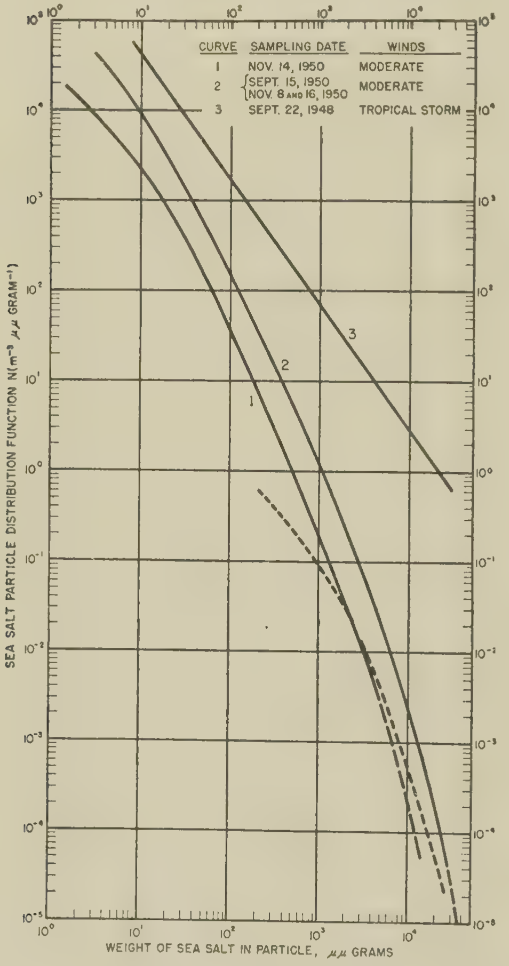

FIG. 5. Smoothed distribution-function curves (1 and 2), taken from observations of sea-salt particle-weight distributions shown in figs. 1–4. Line 3 shows smoothed distribution function of salt particles sampled in tropical storm. Dashed curve shows distribution of salt-particle weight and number, computed from distribution of raindrop number and diameter (fig. 6) and from assumed values for rain-water chlorinity (fig. 7).

5. Correlations of distribution curves for number and weight of salt particles in air, and drop size and salt content of rain waters

Salt particles.—Smoothed distribution curves for the salt particles sampled during moderate and strong winds are shown in fig. 5. Line 3 is based on measurements of particles sampled on 1-mm wide slides in a tropical storm (Woodcock, 1950a), and is included here to suggest the maximum weight and number which may be present in the lower air over the sea. Further measurements are needed during storm conditions, to extend observations to the larger particles. Lines 1 and 2 represent the minimum and average distribution of particles of salt sampled at sub-cloud levels during moderate winds.

Raindrop sizes.—Many observations have been made of the distribution of drop sizes in rains. Fig. 6 is, in part, a reproduction from a study by Marshall and Palmer (1948) and gives an average of the data obtained by these writers and by Laws and Parsons (1943). The dashed lines in this figure represent the distribution of raindrop size at rain intensities of 25, 5 and 1 mm/hr. The unbroken lines represent drop sizes computed from the weights of sea-salt particles and are discussed below.

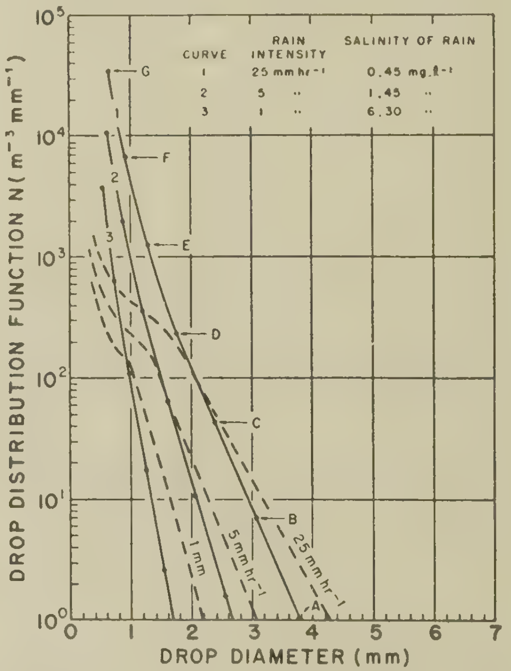

FIG. 6. Dashed lines show variations in distribution of raindrop size at rain intensities of 1, 5 and 25 mm/hr, as given by Marshall and Palmer (1948). Numbered unbroken lines 1, 2 and 3 represent drop-size distribution computed from weights of sea-salt particles given by smoothed distribution-function curve 1 of fig. 5, and from assumed distribution curve 1 for Cl of rains of varying intensity (see fig. 7).

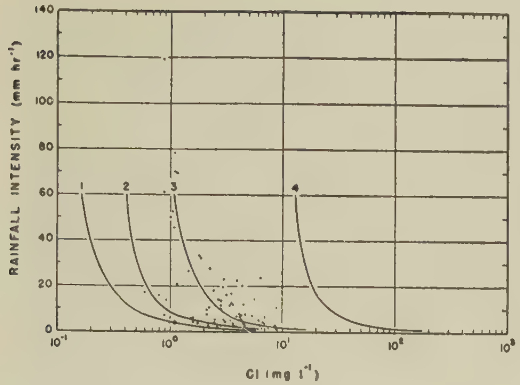

FIG. 7. Black dots represent observed chlorinities in rains of different intensities in southern Florida and Hawaii. Lines 1, 2, 3 and 4 are assumed variations which would be observed if all of chlorides present in rains were derived from larger salt particles found in atmosphere in one of these regions (see fig. 5).

Salt in rainwaters.—Many measurements have been made of the chlorides present in rainwaters, but none of them have clearly related chlorinity to rain intensity. The black dots in fig. 7 represent some measurements of chlorides in rains of various intensities. These preliminary data represent rains from shower clouds in the trade-wind regions of Florida and Hawaii. Many of the rain samples were taken within the clouds, at a height of 900 m, on the northeastern slope of Mt. Haleakala, T. H. A stainless steel funnel of 0.5 m^2 area was used to catch the rain, and sampling durations were from 15 to 300 sec.

A decrease in salt content of rain waters with increased rain intensity, barely suggested by the data in fig. 7, may be due to fundamental processes occurring within the rain-producing clouds. These processes are discussed in the following study of the distribution curves in figs. 5, 6 and 7. In fig. 7, the curved lines represent assumed distributions of chlorides in rains of various intensities. The observed points will be discussed again below

Correlations of salt particles, raindrops and rain salt.—Suppose that all the salt particles weighing $1.3 \times 10^4 \mu\mu g$ (see fig. 5, lower end of line 1)[4] are within a cloud and have become cloud droplets[5] due to condensation processes. Now suppose that more water is added to these droplets, for instance by coalescence with other numerous water droplets, until the concentration of salt in them is equal to that given by curve 1 in fig. 7 for a rate of rain of 25 mm/hr [*i.e.*, about 0.25 mg Cl/l (salinity 0.45 mg/l)]. At this concentration, the droplets become as large as raindrops and are similar in size and number to a value given by Marshall and Palmer (1948) for a rainfall rate of 25 mm/hr (see point A on distribution line 1 of fig. 6). Equation (2), below, was used in computing the drop sizes.

If the salt particles weighing $7 \times 10^3 \mu\mu g$ (see fig. 5, line 1, at the number 1×10^{-3} m^{-3}) become cloud droplets and are similarly diluted, the drop size and the number of these drops again falls near the distribution line given by Marshall and Palmer for a rain rate of 25 mm/hr (see point B, fig. 6). Other nuclei of decreasing weight and increasing number on line 1 (fig. 5) are similarly represented by the letters C, D, E, F and G on fig. 6.

When these salt particles are diluted within a cloud, to the average concentration given by curve 1 in fig. 7 for a rate of rainfall of 5 mm/hr [*i.e.*, a concentration of about 0.8 mg Cl/l (salinity 1.45 mg/l)], the resulting drops have a size distribution represented by the unbroken line 2 in fig. 6. Similarly, unbroken line 3 on this figure represents the sizes of the drops formed on these salt particles at the concentration obtaining in rain waters at a rain intensity of 1 mm/hr [*i.e.*, about 3.5 mg Cl/l (salinity 6.3 mg/l)].[6] If this process is reversed, and the salt particle weights are computed using the raindrop sizes of Marshall and Palmer and the Cl values assumed on curve 1, a distribution of salt particles represented by the dashed line in fig. 5 is obtained.

Thus, the distribution of sea-salt particles sampled in marine air, and represented by line 1 (fig. 5), suggests that the larger of these particles grow within clouds and eventually reach the earth as raindrops. To use line 2 of fig. 5 in a similar way, and to arrive at a drop-size distribution like that given by Marshall and Palmer, it is necessary to assume the higher concentrations shown by line 2 in fig. 7. Concerning curve 3 of fig. 5, a reasonable extrapolation in the direction of larger size indicates the presence in hurricane winds of 10^{-6} particles m$^{-3}\mu\mu g^{-1}$ as heavy as 2×10^{-6} g. This extrapolation suggests that the relationship of Cl and intensity in tropical-storm rains is approximately that of curve 4, fig. 7, assuming again rain-drop sizes near those of Marshall and Palmer. Curve 3 of fig. 7 would similarly represent rains from an atmosphere containing a distribution of salt particles which would fall between curves 2 and 3, fig. 5.

From the above results, it is suggested that a family of curves similar to those in fig. 7 eventually will be found, each representing rain from an atmosphere containing a characteristic distribution of sea-salt particles.[7]

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[4] The extrapolation of lines 1 and 2 on fig. 5 in the direction of greater particle weight is a reasonable one, based upon the sampling experience discussed in section 9, below.

[5] No samples were taken within the clouds, because of the great difficulty of sampling sparsely distributed droplets in the presence of many other droplets.

[6] It may be significant that most of the range of concentration of sea salts and water necessarily assumed here (*i.e.*, about 0.5 to 6.3 mg/l) is similar to that used by Schaefer (1950) in obtaining large electrical potentials in the freezing of diluted sea-water. This electrical effect is suggested as a mechanism for the generation of thunderstorm electricity (Workman and Reynolds, 1948).

[7] In Japan, Takeuchi (1949) has found that rains from air masses of different origin contain greatly varying quantities of Cl.

The scatter of the observed points in fig. 7 is attributed to time variations in the salt content of the air and to the collection of other salt particles by accretion as the raindrops fall from cloud to earth (see Miyake and Suguira, 1950). The writer is now prepared to measure from aircraft the three quantities, salt-particle size, raindrop size and rainwater chlorinity, near and under shower-producing clouds over the sea. Measurements so made are expected to eliminate much of the error in correlating the above interdependent quantities.

6. Discussion

The indicated distribution of raindrops computed from salt particles and those observed by Marshall and Palmer shows a wide divergence of number among the smaller diameter drops. This is assumed to be due, in part, to a low collection efficiency among the smaller particles as droplets entering a cloud, hence a decreased chance that they may grow to raindrop size by coalescence. This divergence may also be due to losses of the droplets formed on the smaller particles within clouds by coalescence with the larger droplets formed on the larger particles, or to errors in sampling the small raindrops.

In fig. 6, the divergence of the distribution of number of rain and salt drops occurs between the values 10^2 and 10^3 drops $\mathrm{m^{-3}\,mm^{-1}}$. In fig. 5, the curve between 10^{-4} and 10^{-2} $\mathrm{m^{-3}\,\mu\mu g^{-1}}$ represents salt particles weighing 13,000 to $3300\mu\mu\mathrm{g}$ (see line 1). These particles will, shortly after entering a cloud as droplets, have radii ranging from 28 to 44μ and will fall fast enough to begin to grow by accretion in descending through a cloud containing droplets of the usual size-range (see Langmuir, 1948, p. 182). Other drops, represented by the curve in fig. 6 between about 2×10^2 and 3×10^4 $\mathrm{m^{-3}\,mm^{-1}}$, were formed on salt particles weighing 1300 to $60\mu\mu\mathrm{g}$ (see fig. 5, line 1). These particles, shortly after entering a cloud as droplets, will have radii ranging from 20 to 7μ and are less likely to grow significantly by accretion because their "collection efficiency" is low. In fact, many of them

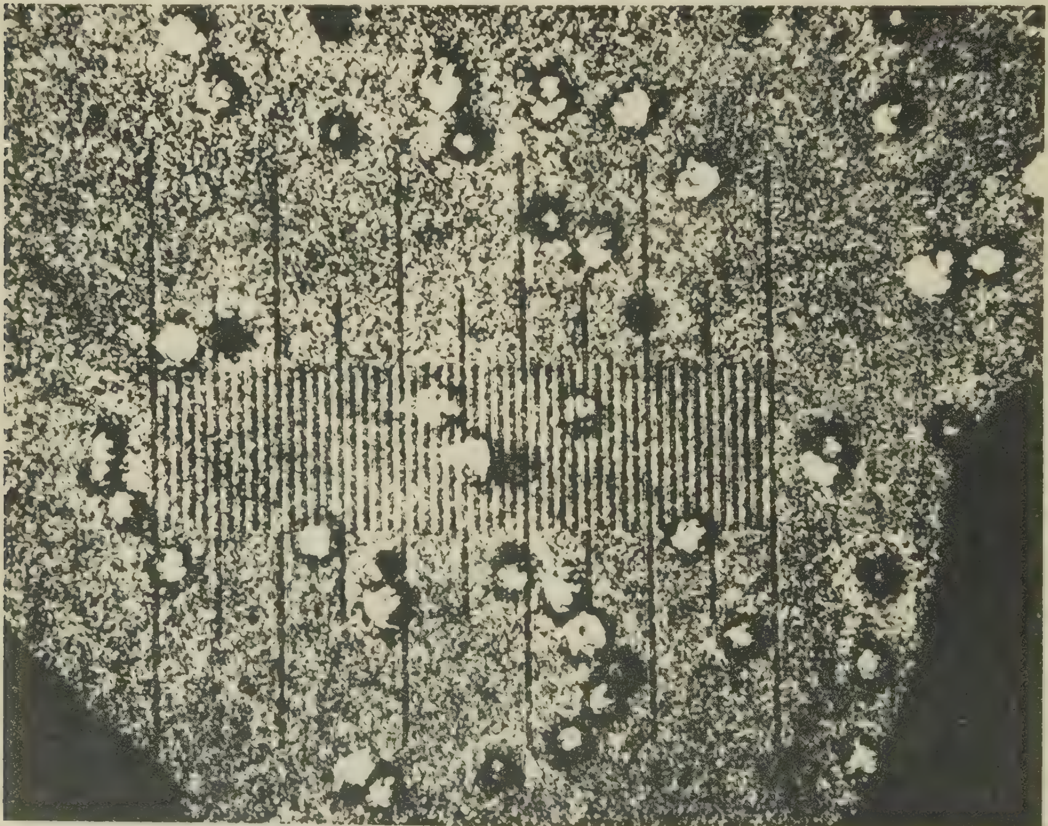

FIG. 8. Photomicrograph of impact discs formed by cloud droplets on surface of smoked glass slide. Slide was exposed 1 sec within cumulus cloud, 30 m above cloud base, over sea. Position: 26°N, 80°W. Time: 1040 EST 10 November 1950. Wind: E.Exposure speed: 26.8 m/sec. Altitude: 730 m. Scale: 1 division = 2.6μ.

Table 6. Comparison of the number of cloud droplets observed in a cumulus cloud (see fig. 8) with the number of condensation nuclei present near the sea surface (table 7), the number of large sea-salt particles present at cloud levels (tables 2, 3 and 4), and the estimated number of salt particles which may become raindrops.

	No. cm⁻³ of air
Condensation-nuclei counts near sea surface (average value)	145
Cloud-droplet counts on smoked slides (average value)	50
Total salt particles samples in clear air at cloud levels (average value)	0.4
Estimated salt particles which may become raindrops*	0.001 to 0.005

* Salt particles larger than about 100 $\mu\mu$g sampled in clear air at cloud levels.

are below the "critical radii" at which no accretion occurs (see Langmuir, 1948, table 5).

Thus, the apparent failure of many of the smaller salt particles to form raindrops may be due to their lower "collection efficiency" upon entering a cloud.

Growth of larger cloud elements to raindrop size by coalescence with smaller cloud elements seems generally accepted as a rain-producing mechanism. It is assumed here that the large cloud droplets, formed by condensation on the large salt particles,[8] subsequently coalesce with a great many smaller water droplets in the cloud which have formed on sub-microscopic condensation nuclei. The lower salt concentration associated with increased rain intensity may be due primarily to a greater "distance of fall" of the raindrops within the cloud (Langmuir, 1948), causing coalescence with greater numbers of cloud-water droplets. From Simpson's study (1941b), it would seem that most of the sub-microscopic condensation nuclei on which the numerous cloud droplets form are not sea salt, since an improbably high nuclei-production rate at the sea surface would be required (*i.e.*, about 5×10^4 cm^{-2} sec^{-1}). However, the work of Dessens (1946) suggests a mechanism for the production of great numbers of very small salt nuclei through the shattering of larger crystals attending phase changes from super-saturated droplets in the atmosphere.

The range of the average weight of condensation nuclei given by various writers is very great indeed (see summary by Howell, 1949, p. 138), making questionable the usefulness of estimates of how much salt may be contained in most cloud droplets in the air over the sea. Hence, no estimates are made here of the total weight of salt which might be added to an initially large salt particle due to its coalescence with a great many smaller cloud droplets containing salt. It should be pointed out, however, that the quantity of salt present in the larger particles is sufficient within the range of the data presented here to account for all of the salt found in rain and cloud waters. A further study of the correlation between the larger salt particles and the final raindrop size and salt concentration may give information about the salt present in the numerous cloud droplets.

Table 7. Measurements of condensation nuclei, with a Schultz counter, at increasing distances inland from the east coast of Florida.* Wind: ESE, force 3. 1430 to 1730 EST 11 November 1950.

Distance from windward shore (mi)	Number of counts	Condensation nuclei cm⁻³
0.04	19	145
1.2	23	970
7.0	18	22,300**
16.5	20	5,985

* For further data from this area, see Woodcock (1950b).
** In the city of Coral Gables, Fla.

Table 6 shows the numbers of salt particles sampled over the sea, compared to the number of condensation nuclei and cloud droplets present over the sea. The number of cloud droplets is an average of four samples taken on smoked glass slides (method from Schaefer, 1945) within the base of a cumulus cloud. Fig. 8 shows a photomicrograph of one of these slides.[9] The condensation-nuclei number shown in table 6 is an average of 19 counts made on the beach (see table 7). The total number of salt particles (table 6) is limited, by the impact method of sampling, to particles with weights greater than about 1 $\mu\mu$g. Hence, this quantity is not to be interpreted as indicating that there are not other smaller salt particles present. Table 6 indicates that the number of cloud droplets is much greater than the number of salt particles sampled in clear air at cloud levels, and is near the number of condensation nuclei found a few meters above sea level on the nearby shore.

It is supposed that the increase in condensation nuclei number over land (table 7) causes a greater number of droplets to form in clouds over land as compared to those present in clouds over the sea. The water in land clouds would thus be distributed among many more droplets, reducing the average drop size. This reduction in size may be a factor in accounting for the increase in the heights of rain-producing clouds as marine air moves inland from the Florida east coast to the inland city of Orlando (see Byers, 1949).

7. Conclusions

1. Many large salt particles are present at sub-cloud and cloud levels in marine air over the sea. Passage of this air over 110 km of land produced no great change in the size distribution of these salt particles. This fact suggests that marine winds probably carry these particles many hundreds of kilometers inland (see also Crozier and Seely, 1950).
2. The correlation of the weight distribution of salt par-

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[8] Growth to raindrop size by condensation processes is not considered here, because of the excessive time required.

[9] The 1-sec timing of the exposure of these slides was manual, using the apparatus shown in fig. 11. Later tests with this apparatus showed that, in five trials, the writer's manual timing of 1 sec varied from 0.7 to 1.1 sec, with an average of about 0.8 sec.

ticles over Florida, the assumed distribution of salt in rains of varying intensity, and the distribution of drop size in rains of varying intensity at Ottawa, Canada and Washington, D. C., suggest that the salt particles play an important role in the formation of rain.

3. The similarity of the numbers of the larger salt particles of cloud levels and the numbers of raindrops of appropriate size and salt concentration suggests that the "chain reaction" process pictured by Langmuir (1948) does not necessarily occur in the formation of rain from warm clouds (T > OC). The effects of the presence of these large salt particles upon the production of rain from super-cooled clouds should also be considered, as was recently emphasized by Ludlam (1951).
4. The fact that the Cl content of rain waters may be accounted for through the presence of a relatively small number of large salt particles suggests that most of the cloud drops with which these large particles coalesce are formed on non-saline nuclei, or that they are formed on salt particles which are so small that most of the cloud droplets are a far more dilute salt solution than are the large droplets with which they coalesce.
5. The relationship shown between the weight and number of the larger salt particles and the number, size and chlorinity of rain suggests further that the failure of some large clouds to produce rain may be due to the absence in them of these salt particles. If such is the case, the possibility of inducing precipitation by seeding with appropriate numbers and sizes of sea salt or other particles becomes evident.

8. Methods

The general method used to sample airborne salt, and the laboratory technique which is used to count and weigh the individual salt particles, have already been described in some detail by Woodcock and Gifford (1949).

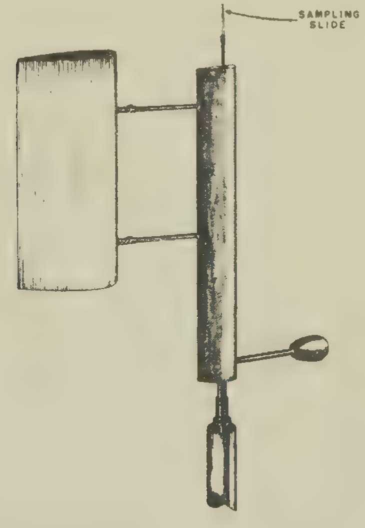

FIG. 9. Device used to expose 1- and 3-mm wide strips of glass at wind and aircraft speeds. Slide at top is extended from and can be drawn down into airfoil tube below.

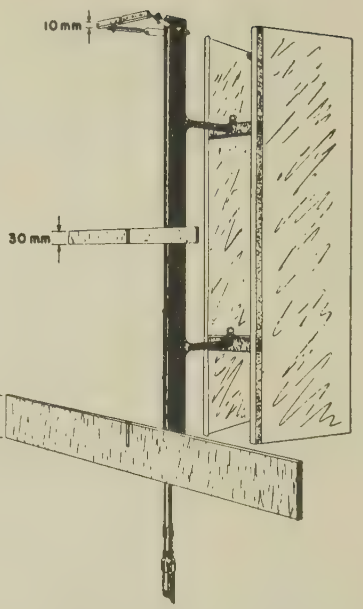

FIG. 10. Wind vane used to hold 10-, 30- and 100-mm wide formica strips normal to wind. Actual sampling surfaces were removable glass slides recessed in middle of strips.

A very brief description is given below of the fundamental sampling and measuring methods used. Some details are given of a modification of the sampling methods already described, which has made it possible to catch large particles which are present in the air in lower numbers. In addition, some methods and new

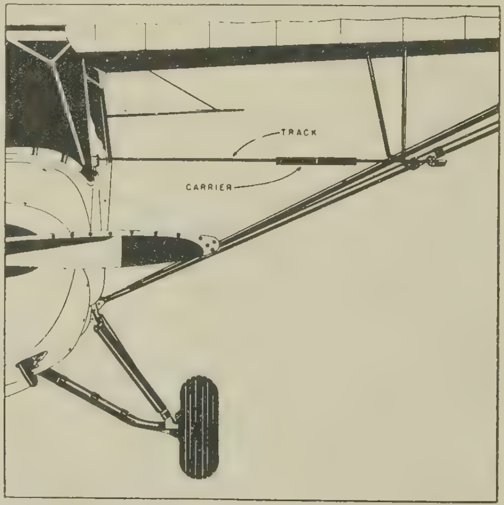

FIG. 11. 10- and 30-mm strips were exposed from light aircraft. On track extending from plane's cabin, carrier, with attached strip and recessed sampling slide, can be hauled out into free air stream and held normal to air flow for required exposure time.

results are given concerning the weight distribution of salt particles in the air, as determined by precipitation. These results are compared to those obtained by impact sampling.

Airborne particles of sea salt have usually been sampled by the writer by exposing 1-mm wide glass slides to the free air stream. The salt particles impinge upon and adhere to the slides and, if liquid, assume a hemispheric form, due to the presence of a hydrophobic film on the glass surface. These slides are then taken to the laboratory and placed in a chamber on a microscope stage, where counts and diameter measurements of droplets are made under controlled temperature and humidity conditions at values near 25C and 90 per cent. Usually at least 500 droplets are measured on each slide. Concentrations of salts in the droplets which form under these conditions were determined by the equal-pressure (isopiestic) method (Glasstone, 1940), and the weights of salt in individual hemispheric droplets were computed from diameter measurements, using the values of Higashi and others (1931) for the specific gravities and the vapor pressures of concentrated sea water.

9. Multi-strip sampling

The triangle symbols on fig. 13 show the approximate range of weight and number of particles sampled on the 1-mm wide glass strips, which had previously been used for almost all sampling (see Woodcock and Gifford, 1949). The slope of a smoothed distribution curve drawn through these points suggested, however, that larger, less numerous particles were also present in the air. The other symbols plotted on this figure, giving sampling results using a modified technique, indicate that there were indeed larger particles present in the air in relatively low numbers.

To catch these large, more sparsely distributed particles, the 1-mm sampling surfaces would have to be exposed, at a given air speed, for a much longer time than that used (see table 1, line 2). However, a prolonged exposure of these small slides is not, in this case, practical, since it will cause an excessive "covering fraction" (see footnote, table 2), and introduce

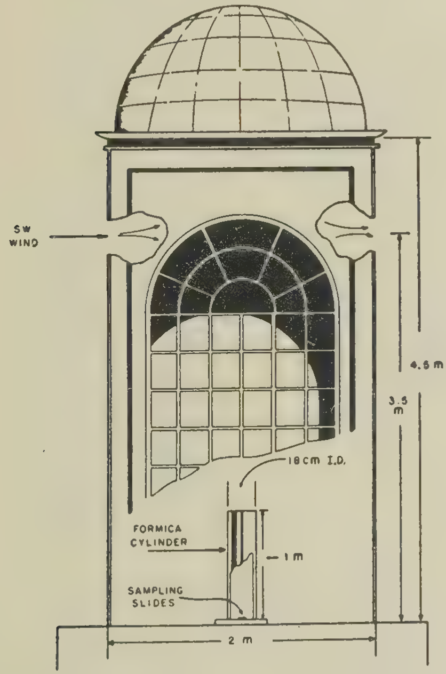

FIG. 12. Cupola of laboratory building was used as precipitation chamber. See text and table 1 for further information.

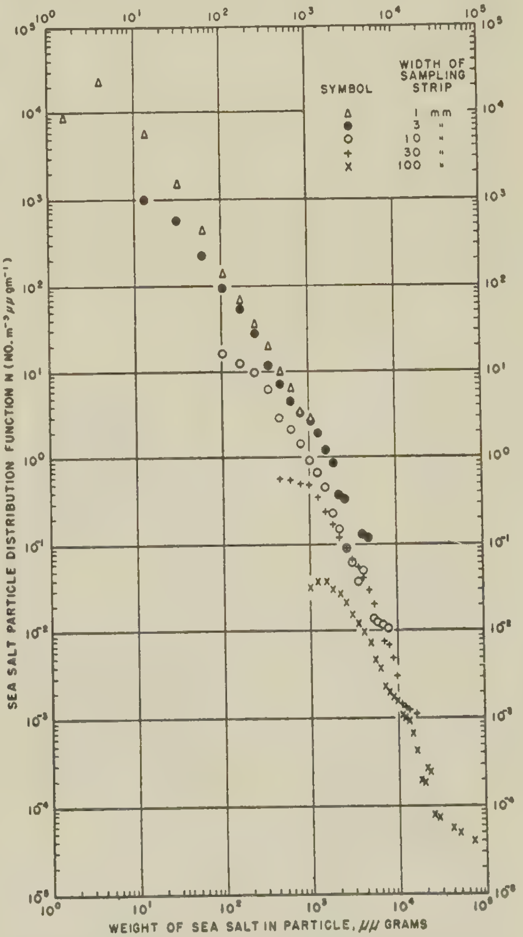

FIG. 13. Sea-salt particle distribution function, using uncorrected data from samples taken 15 September 1950, 5 m above sea surface. Symbols represent various widths of strips used to sample different particle sizes. See table 1, fig. 1 and text for further information.

serious errors in the size- or weight-distribution determinations (Langmuir, 1944, pp. 59–68).

In sampling more nearly the complete range of weight and number of salt particles, several widths of sampling strips have been used. Fig. 10 shows the mounting of the larger of these strips for sampling near the sea surface. In sampling from light aircraft, the 10- and 30-mm sampling strips were mounted on a small track, extending from the fuselage to one of the struts (see fig. 11). The actual sampling surfaces are removable glass slides, recessed near the centers of the formica strips. The apparatus shown in fig. 10 is exposed vertically and the wind vanes hold the sampling surfaces normal to the wind.

Fig. 13 shows the uncorrected distribution of weight and number of salt particles which were deposited on strips from 1 to 100 mm in width, exposed at the end of a dock at Woods Hole. Table 1 gives other information relative to the samples taken on these strips. Fig. 14 shows photomicrographs of some of the salt particles, as droplets (relative humidity: 91 per cent), which were sampled on the strips of various widths. Evaporation of the water in these droplets always reveals a crystalline residue or nucleus (for example, see fig. 16).

Fig. 1 shows the data on fig. 13 corrected for deposition error, according to Langmuir and Blodgett (1945). In fig. 1, it is seen that the smaller particles sampled on the various sizes of slides are in each case eliminated (compare figs. 1 and 13). This is done because the deposition error correction is inaccurate for these particles (see Langmuir and Blodgett, 1945, p. 25 and 25A).

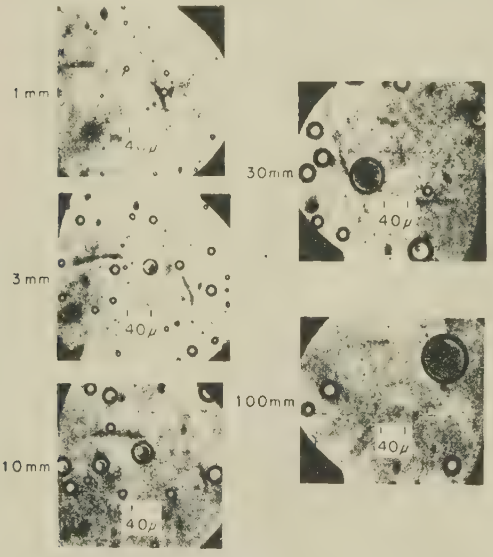

FIG. 14. Photomicrographs of salt particles as hemispheric droplets (relative humidity: 91 per cent) on glass surfaces exposed to wind 15 September 1950. 1- and 3-mm surfaces exposed with device shown in fig. 9; 10-, 30- and 100-mm surfaces exposed on strips shown in fig. 10. Photographed areas on slides selected to illustrate increase in size of particles sampled as width of sampling strips increased. See table 1 for further information about these samples.

The overlapping of counts on the slides of various widths has also been eliminated in fig. 1 and in subsequent sampling (see figs. 2, 3 and 4). In general, observations were not used unless the deposition efficiency for the smaller particles was 0.70 or more. Thus, a selection is made of that portion of the particle-weight spectrum which is most adequately sampled by each width of strip. Selection of sampling-strip widths thus makes possible a selection of the range of weight of aerosol particles to be sampled and avoids excessive covering fractions. The first numbers in table 1, lines 5, 6 and 8, are derived from the counts made on the 1-, 3-, 10-, 30- and 100-mm wide strips. The portion of the particle-weight spectrum selected from the particles measured on each strip is shown by the various symbols in fig. 1.

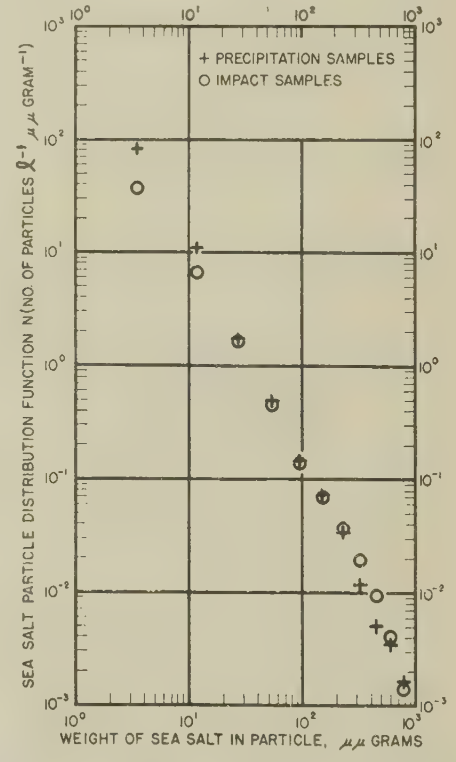

FIG. 15. Comparison of sea-salt distribution as sampled by precipitation and by impact on 15 September 1950. See table 1 and text for further discussion.

The addition of all of the observed weights shown in fig. 1 gives a value of 8.87 $\mu\mu$g cm^{-3} of air (see line 5, table 1). Titration, with a silver-nitrate solution, of the chlorides collected upon other surfaces exposed simultaneously, gave a value of 9.21 $\mu\mu$g cm^{-3}. Thus, the multi-slide, equal-pressure method of measuring the quantity of salt in the air gives a value very close to the value derived by direct titration. Titrations of total chlorides are occasionally used as a test of the validity of the equal-pressure method of determining the weight of the total salts per unit volume of air (see Woodcock and Gifford, 1949, p. 183). Determination of the weight of salt cm^{-3} of air was also made from precipitation counts, using estimates of the particle settling-speeds.

10. Precipitation samples

Precipitation samples of salt particles taken on 15 September 1950 show close agreement with the impact-sampling results. Fig. 15 shows the distribution of salt particles determined from precipitation samples (the +'s), compared to the distribution of particles sampled at the same time by impingement. The difference in the results is insignificant, with the exception of the smaller particles, where deposition-error corrections for impact sampling become questionable (Langmuir and Blodgett, 1945). However, we are concerned here primarily with nuclei larger than 10 $\mu\mu$g.[10] An adequate sampling of particles larger than 775 $\mu\mu$g was not taken by this precipitation sampling, because of insufficient exposure length and the small sampling surface used.

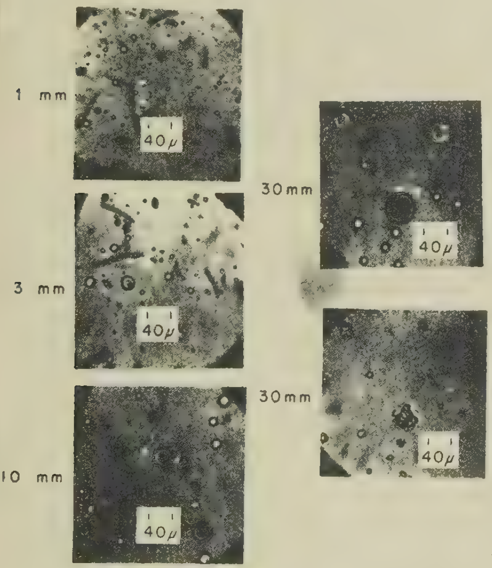

FIG. 16. Photomicrographs of salt particles as hemispheric droplets (relative humidity: 91 per cent) on glass surfaces exposed from aircraft at 1523 m. Table 4 gives further information concerning these samples. Surfaces 1 and 3 exposed with device shown in fig. 9; surfaces 10 and 30 exposed as in fig. 12. Photographed droplets selected to illustrate increase in size of particles sampled as width of sampling strip increased. Second photograph of 30-mm sample made at low relative humidity (40 per cent), to reveal crystalline nature of residue or nucleus.

The simple equation below was used in converting the precipitation counts to numbers cm^{-3}:

$$N = N_c/SR, \tag{1}$$

where N = number of particles cm^{-3} of air, N_c = number of particles counted cm^{-2} of slide surface; S = exposure duration (sec), and R = settling rate of particles.

Settling rate was computed from Stokes' law. Radii of the particles as spheres were from 1.5 to 8 μ, assuming equilibrium at the temperature and relative humidity of the ambient air in the precipitation chamber. Radii of the particles in the air were computed as follows:

$$R = [(W/CD)/(4\pi/3)]^{1/3}, \tag{2}$$

where R = particle radius (μ), W = weight of salt in particle ($\mu\mu$g), C = salt concentration by weight fraction, and D = particle density (the latter two from Higashi and others, 1931).

Precipitation samples were taken in the cupola on the roof of the laboratory, as suggested in fig. 12. This cupola is about 20 m above sea level and near the dock where samples were taken by the impact method. Drifilm-coated, clean glass slides (3 × 30 mm) were placed upon filter paper at the bottom of a cylinder of formica, which stood on the floor of the cupola. A continuous supply of airborne particles flowed through the upper part of the cupola and could rain down within the closed space, through the open end of the cylinder and onto the slides at the bottom. This cylinder, which was shielded from direct solar radiation, reduced the turbulence of the air within the building, so that relatively still air overlay the sampling slides. The relative humidity of the air over the cylinder in the cupola varied between 78 and 81 per cent during the sampling period, while that outside varied from 91 to 93 per cent. The weights of the particles which settled on the exposed slides were subsequently measured by the isopiestic method already described, and the results are given in fig. 15 and table 1 (last column).

Thus, the distribution of particle number and weight, sampled by impact on glass slides and measured by the isopiestic method, is in close agreement with these values determined by precipitation and the isopiestic method. The above agreement and the titration result already given clearly do not prove that fig. 1 represents precisely all the salt particles present in the air during the sampling period. The results in fig. 1 are considered a useful approximation of the correct distribution of weight and number among salt particles, present in the lower air, which occupy the weight range of about 3 to 20,000 $\mu\mu$g. The results of the multi-strip sampling from aircraft (figs. 2, 3 and 4), which are based entirely on the equal-pressure method of measurement, are regarded as an equally useful approximation to the correct weight and number of salt particles present at higher levels.

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[10] The largest condensation nucleus considered by Howell (1949, p. 140), in his study of the growth of cloud drops, was 3 $\mu\mu$g (*i.e.*, 10^{-13} moles). The present study shows that this weight is far from the maximum actually present at cloud levels.

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Contribution No. 567

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RATE OF DISPERSION IN THE WAKE OF A BARGE AT SEA

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(Contribution No. 567 of the Woods Hole Oceanographic Institution)

Abstract--An analysis is presented of the dispersion of a pollutant discharged at sea from a barge. The pollutant in this case contained ten per cent $FeSO_4$, the iron of which proved to be a convenient indicator of dispersion in the sea since it may be observed to concentrations as low as ten parts per billion. The distribution of iron in the wake is related to the rate of discharge and the horizontal mixing coefficient. This relationship provides a means of estimating the rate of discharge of pollutant necessary to meet specific concentration limits.

Introduction--An opportunity to study the dispersion of pollutants in the wake of a barge was afforded by the discharge at sea of acid-iron wastes from the titanium plant of the National Lead Company. In this paper an attempt is made to explain the distribution of the iron in the wake in terms of the rate of discharge and the horizontal mixing coefficients.

The waste material, consisting of about ten per cent $FeSO_4$ and 8.5 pct H_2SO_4, was carried to sea in a specially constructed barge, the Sayreville, which was towed at a speed of six knots. The waste was pumped directly into the wake through two 12-inch pipes mounted on skegs at keel depth at the after end. These outlets were at a depth of 15 ft when the barge was fully loaded, and at six feet when the barge was empty. Each barge load contained about 3000 tons of waste, which was discharged in periods ranging from 80 to 170 min. The distributions of acidity and of iron in the wake were observed in April and July, 1948, and in January, 1950. The quantities discharged, the iron content, and the rate of discharge for each operation are given in Table 1. The description of the distributions has been published by REDFIELD and WALFORD [1951]. The results indicated that the wake continued to spread horizontally for a long time, but reached its greatest depth almost immediately.

Table 1--Discharge characteristics of various waste disposal operations

Date	Waste discharge	Time of discharge	Iron	Discharge[a] rate
1948	ton	minute	pct	g/cm
April 22	2850	165	2.36	20.0
24	2860	180	2.36	18.4
27	2830	145	2.15	20.6
July 24	2830	125	2.18	24.2
27	2860	95	1.58	22.6
1950				
Jan. 4	3120	80	3.52	67.4

[a] Speed of barge = 6 knots.

Methods--The observations were made in April and July from the R. V. Balanus, and in January from the Fish and Wildlife Service vessel Albatross III. Samples were taken in the wake at various times after discharge. The average speed of the barge, 600 ft/min, was used to interconvert distance and time. A stadimeter was used to determine distances up to 6000 ft. Greater distances were estimated from the time after the barge passed an identifiable spot, such as a turn or a position marked by a free-floating buoy discharging fluorescein dye. Samples at various depths were taken with the sea sampler of SPILHAUS and MILLER [1948]. Every effort was made to obtain these samples in the middle of the visible wake. The water samples were analyzed for reducible iron by the dipyridyl method described by COOPER [1935]. The red color formed was measured using a photoelectric colorimeter [FORD, 1950] with green (Wratten 4010) color filters for concentrations less than 0.5 mg/L. A Duboscq colorimeter with appropriate standards was used for greater concentrations.

From the distribution of iron it is possible to evaluate the magnitude of the mixing coefficients required to give the observed distribution. The decrease of the concentration of iron in the wake results from the turbulence induced by the passage of the barge and the normal turbulence of the sea. Although it is impossible to differentiate between these two types of turbulence from the data available, it is possible to estimate the value of the mixing coefficient which describes the joint effects of these two processes.

Three fundamental assumptions are involved in the analysis of the results:

(1) It is assumed that vertical dispersion is instantaneous. It was observed that the waste reached its greatest depth (35 to 70 ft) almost immediately, and little or no further change in depth could be detected.

(2) It is assumed that horizontal diffusion along the axis of the wake can be neglected. Each unit length of the wake received the same original concentration of waste. The wakes were very long and narrow, and the longitudinal gradients were very much less than the transverse gradients.

(3) It is assumed that the distribution of waste along lines perpendicular to the axis was in accordance with the normal curve of distribution. It was impossible to check this assumption because of the difficulty of determining the position of the samples relative to the center of the wake.

The effect of these assumptions is to treat the wake as though all of the iron discharged were concentrated along the median line of the wake at zero time. The problem is thus similar to that discussed by **MUNK, EWING,** and **REVELLE** [1949]. The quantity of iron (y) in a column of water a square centimeter in cross section is given by the usual equation for normal distribution

$$y = (N/\sigma \sqrt{2\pi})\, e^{-1/2[(x-m)/\sigma]^2} \qquad (1)$$

in which N represents the grams of iron discharged per centimeter of barge travel, σ is the standard deviation, and (x - m) is the distance, in centimeters, along a line perpendicular to the axis of the wake between x, the point of observation, and m, the location of the median concentration.

In the middle of the wake, where x = m, the above equation reduces to

$$y = N/\sigma \sqrt{2\pi} \qquad (2)$$

From Fick's equation the following relationship between the standard deviation and the mixing coefficient K was derived by **EINSTEIN** [1905]

$$d\sigma^2/dt = 2K \qquad (3)$$

This implies that the mixing coefficient is independent of the dimensions of the mixing field σ. **RICHARDSON** and **STOMMEL** [1948] and others have shown that this is not true in a fluid medium. Within the range covered by our observations, however, the use of this equation seems justifiable.

The quantities of iron in a column of water one square centimeter in cross section observed in the wake after various periods of time are given in Table 2. If the postulated distribution

Table 2--Quantity of iron in the wake of the discharge barge Sayreville

April, 1948			July, 1948			January, 1950		
Time	$1/\sqrt{t}$	Iron	Time	$1/\sqrt{t}$	Iron	Time	$1/\sqrt{t}$	Iron
sec		mg/cm^2	sec		mg/cm^2	sec		mg/cm^2
15	0.25	51.3	36	0.166	21.2	28	0.189	5.4
44	0.15	28.5	105	0.097	18.5	33	0.174	22.1
75	0.115	6.7	120	0.091	18.3	81	0.111	8.7
113	0.094	6.3	255	0.063	2.1	81	0.111	24.5
143	0.083	6.0	300	0.058	10.6	142	0.084	0.9
157	0.080	12.3	1,200	0.029	2.1	135	0.086	26.0
195	0.071	11.6	1,320	0.028	0.8	218	0.068	16.8
240	0.064	10.2	1,800	0.024	2.4	291	0.059	0.5
240	0.064	7.3	3,900	0.016	0.2	330	0.055	7.1
750	0.036	4.0	14,400	0.008	0.3	600	0.041	8.1
3,300	0.017	1.4	16,200	0.008	0.4	960	0.032	1.6
12,000	0.009	1.0	36,000	0.005	0.15	1,320	0.028	0.1
			41,500	0.005	0.17	1,650	0.025	5.4

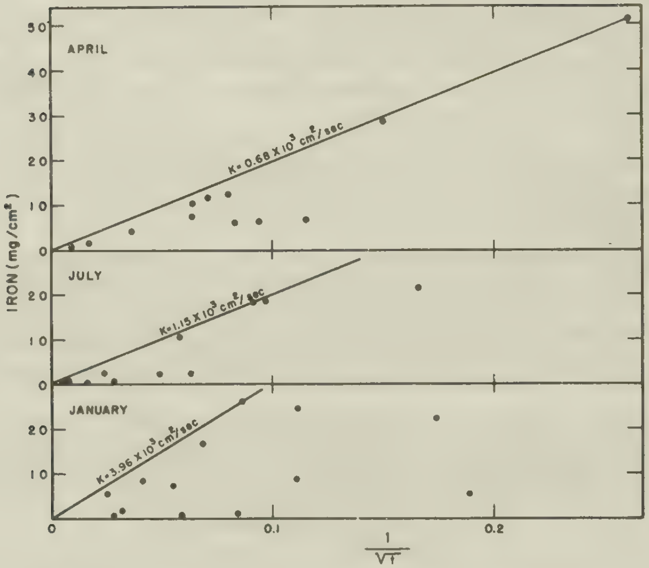

Fig. 1--Relation of iron concentration to mixing time

perpendicular to the axis of the wake applies, the median quantity should be proportional to the reciprocal of the square root of time. The data are presented in this way in Figure 1. The lines drawn in this figure are in accordance with the equation

$$y = (N/2\sqrt{K\pi}) \cdot 1/\sqrt{t} \qquad (4)$$

which is a combination of (2) and the integral of (3) assuming the constant of integration to be zero at zero time. These lines correspond to the minimum value of the mixing coefficient necessary to describe the distribution for each of the sets of observations.

A large proportion of the observed concentrations are less than those predicted by (4). It has been mentioned that it was impossible to determine the exact location of the samples relative to the axis of the wake, though every effort was made to take the samples in the center of the visible axis. The low values are probably attributable to the fact that the ship was not in the center when the samples were taken. As shown in (1), the concentration decreases rapidly as one leaves the center line, that is, when $x - m$ increases.

The most valid observations are those which lie close to the lines drawn in Figure 1. The concentrations selected as giving a reasonably good correspondence with the theory are underlined in Table 2, and the mixing coefficient for each is given in Table 3. The selection is obviously very subjective, but the uncertainty of the location of the samples relative to the center of the wake makes any mixing coefficient computed from the other data meaningless. The average of the mixing coefficients for the selected concentrations was about 2×10^3 cm²/sec in April and July, and nearly 7×10^3 cm²/sec in January.

Several conditions might have contributed to the greater mixing coefficient observed in January. The rate of discharge at this time was about threefold greater than the rates in April and July. If the quantity of iron in the wake is directly proportional to the rate of discharge, as in (2), this should not affect the value of the mixing coefficient. The weather was moderate during all of the operations. At the time of the January observations the wind force varied from 1 to 2. In April and July wind forces of 1 to 3 obtained during the operations. It may be significant that the disposal operations in April and July were located in water ranging up to 185 ft in depth, whereas in January the discharge location was in water where the maximum depth was 80 ft [REDFIELD and WALFORD, 1951]. The most likely explanation, however, may be found in the fact that the vertical stability of the water column was less in January than in April or July. The salinity, temperature, and density (σ_t) of the water at the three times are shown in Figure 2. The cross bars on the density curves show the depth to which the water was contaminated with iron in the wake.

Table 3--Mixing coefficients required to give observed quantities of iron in the wake of the barge

Date	Rate of discharge	Iron	Time	Standard deviation	Mixing coefficient
1948	g/cm	mg/cm^2	sec	cm	cm^2/sec
April	18.4	51.3	15	143	0.7×10^3
	20.6	28.5	44	288	1.0×10^3
	18.4	12.3	157	595	1.2×10^3
	20.6	11.6	195	709	1.4×10^3
	20.6	10.2	240	805	1.5×10^3
	20.6	4.0	750	2,050	3.0×10^3
	20.6	1.4	3,300	5,860	5.6×10^3
	20.0	1.0	12,000	7,950	2.7×10^3
July	24.2	18.5	105	524	1.3×10^3
	24.2	18.3	120	530	1.2×10^3
	22.6	10.6	300	860	1.2×10^3
	22.6	2.4	1,800	3,860	3.9×10^3
1949					
January	67.4	24.5	81	1,090	7.4×10^3
	67.4	26.0	135	1,030	4.0×10^3
	67.4	16.8	218	1,590	5.8×10^3
	67.4	8.1	600	3,300	9.4×10^3
	67.4	5.4	1,650	4,950	7.5×10^3

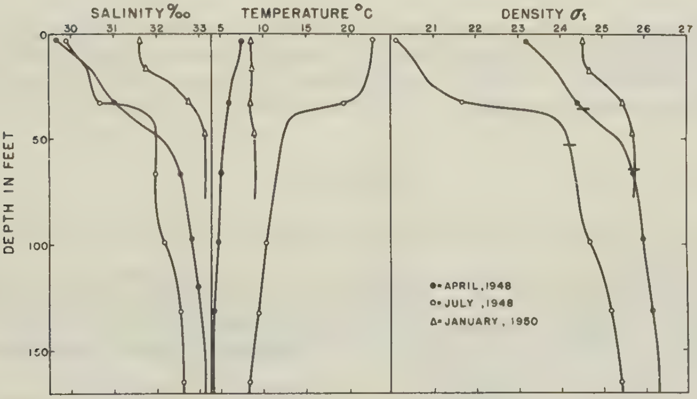

Fig. 2--Salinity, temperature, and density of the water during the three test periods

Discussion--No claim is made for the accuracy of the mixing coefficients computed in this paper. The inaccuracies of sampling, particularly the difficulty of determining whether the samples were collected in the center of the wake, introduce large uncertainties in the estimates.

It might be expected that the mixing coefficient would be very large near the barge because of the turbulence of the wake. There is no clear evidence for any such difference, though there may be a suggestion of it in the July and January data. The mixing coefficients do show a tendency to increase with increasing time, and thus with the dimensions of the mixing field, which also increases with time. This increase would be expected from the results demonstrated by **RICHARDSON** and **STOMMEL** [1948]. It should be mentioned that the accuracy of locating the center of the wake was best when close to the barge. It is possible that the larger coefficients obtained for greater distances indicate that these samples were not in the axis of the wake.

The value of these results lies in the fact that they make it possible to estimate the distribution to be expected for similar operations if the rate of discharge is known. To facilitate such predictions Figure 3 has been prepared to show the effects of various mixing coefficients and

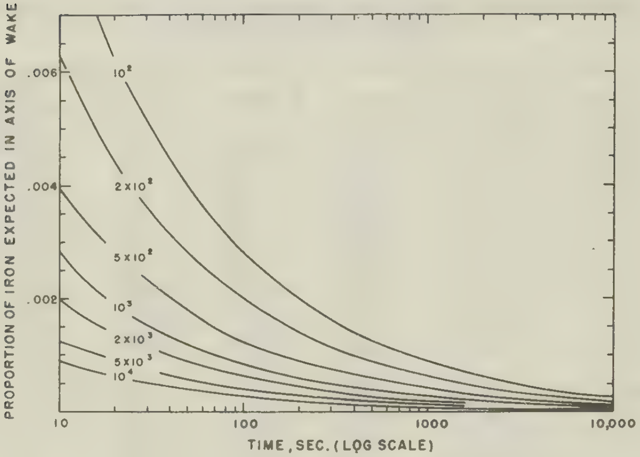

Fig. 3--Curves for forecasting mixing

times on the proportion of the discharged pollutant to be expected in the axis of the wake. This proportion, when multiplied by the discharge rate (g/cm), will give the quantity (g/cm^2) to be expected. Since the rate of discharge is the only variable which can be controlled in the operation, the rate necessary to meet specific concentration limits can be selected. General application of the method is subject to uncertainty since little is known about the value of the mixing coefficients to be expected.

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A Theoretical Model for Sound Scattering by Marine Crustaceans*

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With an eye to application in the investigation of sound scattering by marine life, the reflectivity of a spherical elastic shell containing a fluid is studied. It is found that for incident wavelengths of the order of magnitude of the sphere, the behavior for thin shells is similar to that of the fluid sphere alone. For longer wavelengths a correction is computed, good to terms in the first power of the thickness:diameter ratio of the shell.

INTRODUCTION

IN the investigation of reverberation from the ocean's deep scattering layer (false bottom echo), the sound scattering from marine life has received considerable attention.[1] An attempt is made here to assess the effect of the carapace on the scattering properties of a marine crustacean, by studying the reflectivity of a spherical elastic shell containing a fluid.

The problem of the scattering from a fluid sphere imbedded in an infinite fluid medium was solved by Rayleigh[2] for nonviscous fluids, in terms of infinite series useful only at low frequencies, i.e., wavelengths large compared with the dimensions of the sphere. It has been solved for viscous fluids, as well as for an elastic solid sphere, by Epstein[3] in terms of the Heine functions (spherical Bessel and Hankel functions). Using the recent tabulation of these functions,[4] Anderson[5] has published graphs (for perfect fluids) of the differential and total reflectivities as functions of frequency and of the acoustic properties of the two fluids (relative densities and sound velocities). It will be shown here that the reflectivity of the fluid encased in a thin shell is substantially identical with that of the fluid sphere alone, when the incident wavelength is of the order of the radius of the sphere, and somewhat less than the latter in the Rayleigh region.

STATEMENT OF THE PROBLEM

Let a plane monochromatic sound wave, propagated in an infinite nonviscous fluid, meet a spherical object consisting of a nonviscous fluid encased in a thin elastic solid shell. The object is considered in equilibrium in the absence of the sound wave, i.e., gravity is neglected: There are no weight or buoyancy forces.

Notation: R = radius of the middle plane of the shell, $2h$ = thickness of the shell, $\omega/2\pi$ = frequency of the incident sound, k_1 = bulk modulus of the outside fluid, k_2 = bulk modulus of the shell, k_3 = bulk modulus of the inside fluid, μ = rigidity modulus of the shell, ρ_1 = density of the outside fluid, ρ_2 = density of the shell, ρ_3 = density of the inside fluid, and $\lambda = k - \frac{2}{3}\mu$.

The equation of motion of an elastic body for small displacements, in terms of the vector displacement $\mathbf{S}$ is

$$(k+\tfrac{1}{3}\mu)\nabla\nabla\cdot\mathbf{S}+\mu\nabla^2\mathbf{S}=\rho\partial^2\mathbf{S}/\partial t^2. \qquad (1)$$

For monochromatic incident sound,

$$\mathbf{S}=\mathbf{s}e^{-i\omega t},$$

since transient behavior is not of interest here. Separating into irrotational and solenoidal parts,

$$\mathbf{s}=-\nabla\Phi+\nabla\times\mathbf{A},$$

where

$$\nabla\cdot\mathbf{A}=0.$$

Then the equation of motion is satisfied if

$$\nabla^2\Phi+\kappa^2\Phi=0 \qquad (2)$$

and

$$\nabla^2\mathbf{A}+\bar{\kappa}^2\mathbf{A}=0 \qquad (3)$$

separately, where $\kappa^2=\omega^2\rho/(k+4\mu/3)$ and $\bar{\kappa}^2=\omega^2\rho/\mu$. Note that $\mathbf{A}$ is nonzero only in the shell; i.e., a nonviscous fluid is incapable of supporting a solenoidal wave.

Choose a spherical coordinate system (r, θ, φ) with origin at the center of the sphere and polar axis in the direction of the sound source. From symmetry, only the azimuthal component of $\mathbf{A}$ is seen to be nonvanishing; thus there remain two scalar equations:

$$\frac{\partial}{\partial r}\left(r^2\frac{\partial\Phi}{\partial r}\right)+\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\Phi}{\partial\theta}\right)+\frac{1}{\sin^2\theta}\frac{\partial^2\Phi}{\partial\varphi^2}+\kappa^2r^2\Phi=0, \qquad (4)$$

$$\frac{\partial}{\partial r}\left(r^2\frac{\partial A}{\partial r}\right)+\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial A}{\partial\theta}\right)+\frac{1}{\sin^2\theta}\frac{\partial^2 A}{\partial\Phi^2}+\left(\kappa^2r^2-\frac{1}{\sin^2\theta}\right)A=0. \qquad (5)$$

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* Woods Hole Oceanographic Institution Contribution No. 569.

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[1] University of California, Division of War Research, "Stratification of sound scatterers in the ocean," UCDWR File Report No. M397 (February 16, 1946). J. B. Hersey and H. B. Moore, Trans. Am. Geophys. Union 29, 341 (1948).

[2] Lord Rayleigh, *Theory of Sound* (Dover Publications, New York, 1945), Vol. II, Sect. 334.

[3] Paul S. Epstein, "On the absorption of sound waves in suspensions and emulsions," *Theodore von Kármán Anniversary Volume* (1941), p. 162.

[4] *Tables of Spherical Bessel Functions* (Columbia University Press, New York, 1947).

[5] Victor C. Anderson, J. Acoust. Soc. Am. 22, 426 (1950).

Separation of variables results in Legendre equations for the angular function (P_n, P_n', respectively), spherical Bessel functions for the radial function. Finiteness conditions limit the values of the indices n to integers. Thus the most general solution is an infinite series in n.

BOUNDARY CONDITIONS

Let the incident wave be[6]

$$\Phi_0=e^{-i\kappa_1 r\cos\theta}\equiv\sum_{n=0}^{\infty}(-i)^n(2n+1)j_n(\kappa_1 r)P_n(\cos\theta), \quad (6)$$

where

$$j_n(x)=\left(\frac{\pi}{2x}\right)^{\frac{1}{2}}J_{n+\frac{1}{2}}(x) \quad \text{(spherical Bessel function).}$$

The scattered wave must approach, at large distances, the form of an outgoing spherical wave; hence it will have the form

$$\Phi=\sum_{n=0}^{\infty}(-i)^n(2n+1)B_n\zeta_n(\kappa_1 r)P_n(\cos\theta), \quad (7)$$

where

$$\zeta_n(x)\equiv j_n(x)+in_n(x) \quad \text{(spherical Hankel function),}$$

$$n_n(x)\equiv(-)^{n+1}\left(\frac{\pi}{2x}\right)^{\frac{1}{2}}J_{-n-\frac{1}{2}}(x)$$

(spherical Neumann function).

The wave in the inside fluid must have finite amplitude at the origin; hence

$$\Phi_3=\sum_{n=0}^{\infty}(-i)^n(2n+1)E_n\,j_n(\kappa_3 r)P_n(\cos\theta). \quad (8)$$

In the shell the more general solution must be assumed:

$$\Phi_2=\sum_{n=0}^{\infty}(-i)^n(2n+1)$$
$$\times[C_n\,j_n(\kappa_2 r)+D_n\,n_n(\kappa_2 r)]P_n(\cos\theta), \quad (9a)$$

$$A=\sum_{n=0}^{\infty}(-i)^n(2n+1)$$
$$\times[F_n\,j_n(\bar{\kappa}r)+G_n\,n_n(\bar{\kappa}r)]P_n'(\cos\theta). \quad (9b)$$

The physical boundary conditions are as follows: (1) The displacements normal to the boundary must be continuous. (2) The fluid pressure at the boundary must equal the normal stress in the shell. (3) The tangential stress in the shell must vanish at the boundary. Applying these conditions at the boundaries $r=R+h$ and $r=R-h$ yields the following six equations:

$$\kappa_1\left[\frac{\partial\Phi_0}{\partial(\kappa_1 r)}+\frac{\partial\Phi_1}{\partial(\kappa_1 r)}\right]=\kappa_2\frac{\partial\Phi_2}{\partial(\kappa_2 r)}-\frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(A\sin\theta)$$

$$\text{at}\quad r=R+h \quad (10a)$$

$$\kappa_3\frac{\partial\Phi_3}{\partial(\kappa_3 r)}=\kappa_2\frac{\partial\Phi_2}{\partial(\kappa_2 r)}-\frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(A\sin\theta)$$

$$\text{at}\quad r=R-h \quad (10b)$$

$$k_1\kappa_1^2(\Phi_0+\Phi_1)=\lambda\kappa_2^2\Phi_2$$
$$+2\mu\left\{-\kappa_2^2\frac{\partial^2\Phi_2}{\partial(\kappa_2 r)^2}+\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left[\sin\theta\left(\frac{\bar{\kappa}}{r}\frac{\partial A}{\partial(\bar{\kappa}r)}-\frac{A}{r^2}\right)\right]\right\}$$

$$\text{at}\quad r=R+h \quad (10c)$$

$$k_3\kappa_3^2\Phi_3=\lambda\kappa_2^2\Phi_2$$
$$+2\mu\left\{-\kappa_2^2\frac{\partial^2\Phi_2}{\partial(\kappa_2 r)^2}+\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left[\sin\theta\left(\frac{\bar{\kappa}}{r}\frac{\partial A}{\partial(\bar{\kappa}r)}-\frac{A}{r^2}\right)\right]\right\}$$

$$\text{at}\quad r=R-h \quad (10d)$$

$$-2\frac{\partial}{\partial\theta}\left[\frac{\kappa_2}{r}\frac{\partial\Phi_2}{\partial(\kappa_2 r)}-\frac{\Phi_2}{r^2}\right]$$
$$-\left[\bar{\kappa}^2\frac{\partial^2 A}{\partial(\bar{\kappa}r)^2}-\frac{2}{r^2}A\right]+\frac{1}{r^2}\frac{\partial}{\partial\theta}\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}(A\sin\theta)\right]=0$$

$$\text{at}\begin{cases} r=R+h & (10e)\\ r=R-h. & (10f)\end{cases}$$

This system yields six equations for every value of n, determining the six unknown coefficients B_n, C_n, D_n, E_n, F_n, G_n.

PHYSICAL INTERPRETATION

This article will choose as a measure of the scattered sound a "reflectivity coefficient" R_θ defined as the ratio of the scattered wave amplitude at angle θ to the amplitude which the scattered wave would have if the obstacle reflected geometrically, i.e.

$$R_\theta=|\Phi_1|/|\Phi_{\text{geometrical}}|. \quad (11)$$

For backward scattering ($\theta=0$) this becomes[7]

$$R_0=\frac{2}{b_1}\left|\sum_{n=0}^{\infty}(-)^n(2n+1)B_n\right|, \quad (12)$$

where

$$b_1=\kappa_1(R+h).$$

High Frequencies

Consider first the case where b_1 is of the order of unity. Here the Heine functions may be considered slowly-varying, i.e., changes in them are small compared to unity for small fractional changes in their arguments.† Solving for B_n by Cramer's rule, $B_n=\Delta_B/\Delta$; in both determinants subtract the even-numbered rows from the odd. Assuming a thin shell ($h/R\ll 1$), neglect higher powers of h/R beside the first. Expand each determinant along its first column, the remaining fifth-order determinants along their second and first rows, respectively. Then

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[6] For proof of this identity, see, for example, Rayleigh, reference 3, Vol. II, p. 273.

[7] For proof, see reference 5, p. 428.

$$B_n=\frac{\begin{vmatrix} b_1 j_n'(b_1) & a_3 j_n'(a_3) \\ k_1 b_1^2 j_n(b_1) & k_3 a_3^2 j_n(a_3)\end{vmatrix}}{\begin{vmatrix} b_1 \zeta_n'(b_1) & -a_3 j_n'(a_3) \\ k_1 b_1^2 \zeta_n(b_1) & -k_3 a_3^2 j_n(a_3)\end{vmatrix}}, \qquad (13)$$

where

$$a_3=\kappa_3(R-h).$$

It will be noticed that this expression is independent of the material of the shell, and reduces for $h=0$, to that for the fluid sphere alone, as is required. Considering the shell material to be identical alternately with the inside and with the outside fluids shows the character of the approximation. It becomes invalid when h/R is an appreciable fraction of the period of oscillation of the Heine functions; i.e., the high frequency limitation is $h/R\ b_1\ll 1$.

In the cases of interest in this laboratory, $h/R\cong 1/100$, making the fluid sphere approximation good for $b_1\ll 100$. It should be remarked that for arguments greater than 10, the theoretical expressions become clumsy, because of the large number of terms having appreciable magnitude and the resulting complicated angular dependence of R_θ. This also diminishes the value of the theory in interpreting the results of experiments, as the finite size of the receiver limits angular resolution.

Experimental verification of the general conclusions above is nevertheless found in laboratory tank experiments by Tamarkin[8] with cylindrical obstacles. (The applicable theory is analogous.) For $b_1\cong 30$, using a small microphone (high resolution), he reports negligible effect of a polyethylene shell with $h/R=0.003$, around a water cylinder.

Low Frequencies

For b_1 substantially less than unity, $n_n(b)-n_n(a)$ may no longer be considered small. But here only the first two terms of the incident wave (in j_0 and j_1) make appreciable contributions, hence B_0 and B_1 suffice in computing R_θ (Rayleigh approximation). For $h=0$ (fluid sphere),

$$(R_0)_{h=0}=\tfrac{2}{3}b_1^2\left|\left(1-\frac{k_1}{k_3}\right)+\frac{3}{2}\left(\frac{1-\rho_1/\rho_3}{1+\frac{1}{2}\rho_1/\rho_3}\right)\right|, \qquad (14)$$

showing the familiar dependence of scattering cross section on ω^4R^6 for small scatterers. Letting

$$R_0=(R_0)_{h=0}[1+\delta],$$

the fractional difference

$$\delta=\frac{h}{R}\,\frac{U+V+W}{\left(1-\dfrac{k_1}{k_3}\right)+\dfrac{3}{2}\left(\dfrac{1-\rho_1/\rho_3}{1+\frac{1}{2}\rho_1/\rho_3}\right)}, \qquad (15)$$

where

$$U=6\frac{k_1}{k_3}\left(\frac{k_3+4/3\mu}{k_2+4/3\mu}\right)\left(\frac{k_2}{k_1}-1\right),$$

$$V=-3\frac{\rho_1}{\rho_3}\,\frac{\left(1+\dfrac{48}{74+57\lambda/\mu+9\lambda^2/\mu^2}\right)}{(1+\frac{1}{2}\rho_1/\rho_3)^2},$$

$$W=\frac{27}{5}\,\frac{\rho_1\rho_2}{\rho_3^2}\,\frac{\dfrac{36+108\lambda/\mu+77\lambda^2/\mu^2+15\lambda^3/\mu^3}{74+57\lambda/\mu+9\lambda^2/\mu^2}}{(1+\frac{1}{2}\rho_1/\rho_3)^2},$$

neglecting powers of h/R higher than the first.

Inserting values which might be typical for a marine crustacean:

$$k_1:k_2:k_3:\mu=1:5:0.9:2$$

$$\rho_1:\rho_2:\rho_3=1:1.1:0.9$$

$$h/R=1/500,$$

it follows that $\delta=-0.2$.

Thicker Shells

When second and higher powers of h/R are not negligible, a different approach must be made. The method of phase-shifts has been applied by Lax and Feshbach[9] to the scattering of sound by spheres; it permits computation of scattered wave amplitudes (using published tables), provided the acoustic impedance function of the scatterer is known. Specifically,

$$\left(\frac{\partial}{\partial(\kappa_1 r)}[B_n\zeta_n(\kappa_1 r)+j_n(\kappa_1 r)]\right)_{r=R+h}=-\sigma_n(\omega) \qquad (16)$$

where $\sigma_1(\omega)$ is the relative acoustic admittance of the obstacle. For the fluid sphere alone,

$$\sigma_n=-\left(\frac{\rho_1 k_1}{\rho_3 k_3}\right)^{\frac{1}{2}}\frac{j_n'(a_3)}{j_n(a_3)}. \qquad (17)$$

No simple method has been found by the present author of assigning an acoustic impedance function to the obstacle under consideration. Computation would require the successive elimination of the unknowns C_n, D_n, F_n, G_n and has not been attempted.

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† This becomes invalid at low frequencies, where $n_n(x)$ diverges, and at high frequencies, since the period of oscillation becomes constant ($=2\pi$). See below for a discussion of the limits of validity.

[8] Paul Tamarkin, J. Acoust. Soc. Am. 21, 612 (1949).

[9] M. Lax and H. Feshbach, J. Acoust. Soc. Am. 20, 108 (1948).

APPLICATION TO MARINE CRUSTACEANS

On the one hand, the irregular shape of these animals would tend to eliminate the strong flexural modes of vibration of which the sphere is capable. On the other hand, the segmented character of their carapace may permit the low frequency flexural modes possible for a short cylinder.

The viscosity and plasticity of the inside will certainly damp the resonances of the fluid sphere behavior, but will change the frequency characteristics but slightly. A coefficient of viscosity η, for instance, will cause the wave number κ (nondissipative) to be replaced by[10]

$$\kappa=\kappa_{\text{nondissipative}}\left[1+\tfrac{2}{3}i\omega(\eta/k)\right].$$

Dissipation in the shell will be effective at low frequencies, and may even increase the reflectivity for small μ,[11] somewhat spoiling the ω^2 dependence (see section on "Low Frequencies"). The effect of the inhomogeneity of the inside cannot be evaluated; certainly k_3 and ρ_3 must be "suitably chosen" averages.

Experiments now in progress on the backward scattering from controlled distributions of marine animals near the surface[12] are expected to test the usefulness of the considerations advanced above in the interpretation of data on the deep scattering layer, and on volume reverberation in general.

This research was suggested by and carried out under the guidance of Dr. J. B. Hersey. To him and the other members of his research staff, especially Mr. Arthur Voorhis, the author wishes to express his appreciation for many stimulating discussions.

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[10] See reference 3, p. 164.

[11] See reference 9, p. 121.

[12] Paul F. Smith (WHOI, personal communication).

Contribution No. 572

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3.13. RECOGNITION OF THE PRESENCE OF CONVECTIVE CURRENTS WITHIN A NONSATURATED TURBULENT LAYER OF THE ATMOSPHERE[1]

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ABSTRACT

The presence of convective currents in the ground layer of the atmosphere is detected by the magnitude of the correlation coefficient existing between simultaneous values of the air temperature and the roughness of the air. These quantities are measured by a psychrograph and a vertical water-column accelerometer mounted on an airplane flying through the turbulent air. Values of the correlation coefficient are found to depend on the intensity of convection and associated conditions such as stability, cloud cover, height, the interval over which the values are averaged, and the roughness of the air. It is observed that convection in the slightly turbulent air of the "cloud layer" leads to a correlation coefficient approaching unity. In a turbulent stream of air with neutral stability, the coefficient attains only small values (0.0 to 0.2), while in an air mass heated from below higher values (0.4 to 0.8) are found. In extremely turbulent air the coefficient may be low (0.2) in spite of the presence of active convection in the "cloud layer" above the ground layer. These low values are interpreted to mean that convection cannot exist in an unstable ground layer if the turbulence is sufficiently great. The sensitivity of the correlation coefficient to the interval over which the observations are averaged makes it a valuable means of determining the sizes of convecting parcels or cells.

Massachusetts Institute of Technology, Geophysics Research Directorate
Air Force Cambridge Research Center
Cambridge, Massachusetts
December, 1952

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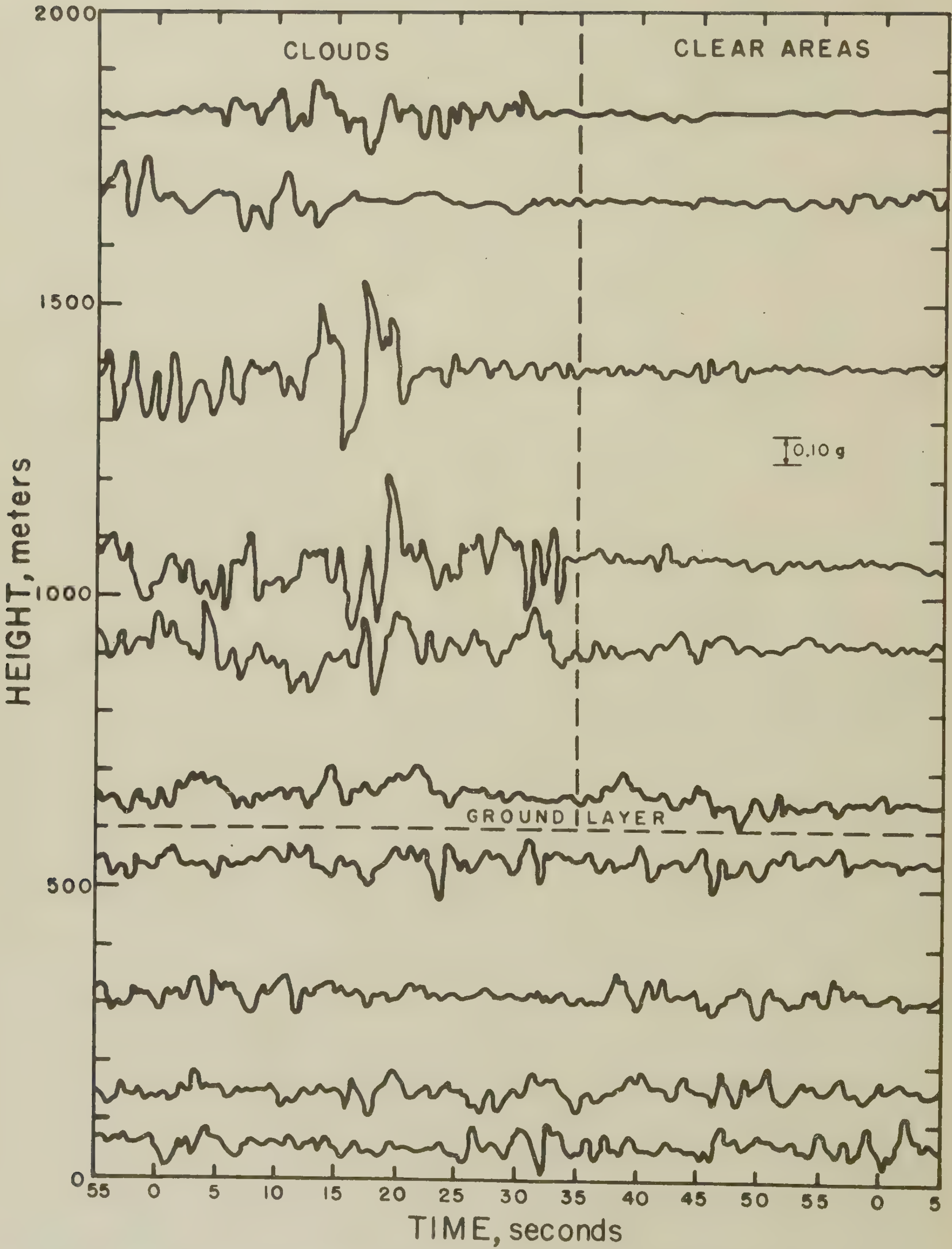

Fig. 3.13.1. Distribution of vertical accelerations imparted to an aircraft in the ground layer and cloud layer of the atmosphere.

3.13.1. INTRODUCTION

One result of many series of observations made at the Woods Hole Oceanographic Institution in air masses moving over warmer water is the compilation of values of the coefficient of turbulent mass exchange. Observations of dry- and wet-bulb temperatures were obtained from airplane flights extending to heights of 2000 m and offshore distances of 150 km. Mixing ratio gradients and rates of flow of water vapor were determined and substituted in the classical diffusion equation to yield the turbulent mass exchange coefficient. As it is desired to study transport by turbulence rather than by convection, which may be considered a special case of turbulence, it must be shown that no convective currents were present in the turbulent stream and contributed to the transport of water vapor. A means of recognizing the existence of convection in a non-saturated, turbulent air stream by use of flight records of an airplane flying through the stream, has been developed and is discussed in the following sections.

The detection problem is attacked with the knowledge that convection creates additional turbulence by the ascent of air, either as a parcel or a cellular circulation, through the air mass. It has been observed repeatedly, see Fig. 3.13.1[2], that the turbulence through a convective cloud consists of greatly increased turbulence throughout the cloud rather than consisting of a sharp zone of turbulence around the boundary of the cloud. In the "cloud layer" of the atmosphere, areas of clouds can be identified from a continuous record of the vertical accelerations experienced by an airplane in flight. In the turbulent ground layer, however, the existence of convection cannot be identified in a like manner. There are numerous areas of slightly increased turbulence evident on an accelerometer record, but these are insufficient for identification as being the result of convection. Another element, temperature, must be considered for the identification of convective currents. Since convective parcels are lighter than the surrounding air, a positive correlation should exist between deviations in the temperature and accelerations whenever convection is initiated in the turbulent stream. The validity of this proposition is tested by comparing the magnitude of the correlation coefficients obtained in air streams containing varying degrees of convective activity.

In discussing particular cases it is essential to state that the quantities used in determining the coefficient are averages over several seconds. During this interval the sounding aircraft travels through many meters of air. The roughness measures are made from the record of a water-column accelerometer, mounted in the airplane, which measures the vertical accelerations imparted to the aircraft by the turbulent air. A quantity called the *turbulence index* and defined as the area enclosed by the envelope of a 10-sec interval of the accelerometer record is used as the measure of the roughness of the air. See Fig. 3.13.2. The air temperature to be coupled with the turbulence index is obtained from a record of the resistance of the dry-bulb thermistor of the airplane psychrograph. An average value of the resistance for 10 sec was reduced to a temperature. Since the plane is flown at a speed of about 30 m/sec, 300 m of air contribute to the mean temperature.

Averages have been computed over other time intervals to investigate any effect of the averaging interval on the magnitude of the correlation coefficient. Running averages have been made from the original 10 sec readings for 20, 40, 80, and 120 sec intervals. The 120 sec interval corresponds to a distance of 3600 m.

Before presenting the correlation coefficient observed in the atmosphere, it is well to discuss the various combinations of gradients of temperature and turbulence frequently encountered and the correlations to be expected from each combination.

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[2] Reproduced from Pap. Phys. Oceanogr. Meteor., Vol. XI, No. 1, Fig. 59.

The first case considered is a purely turbulent stream of heterogeneous fluid with no mean gradient of turbulence or temperature. In such a fluid, regions with any given degree of turbulence have equal probabilities of being either warmer or cooler than the mean. A correlation computed from pairs of values measured in this fluid will approximate zero.

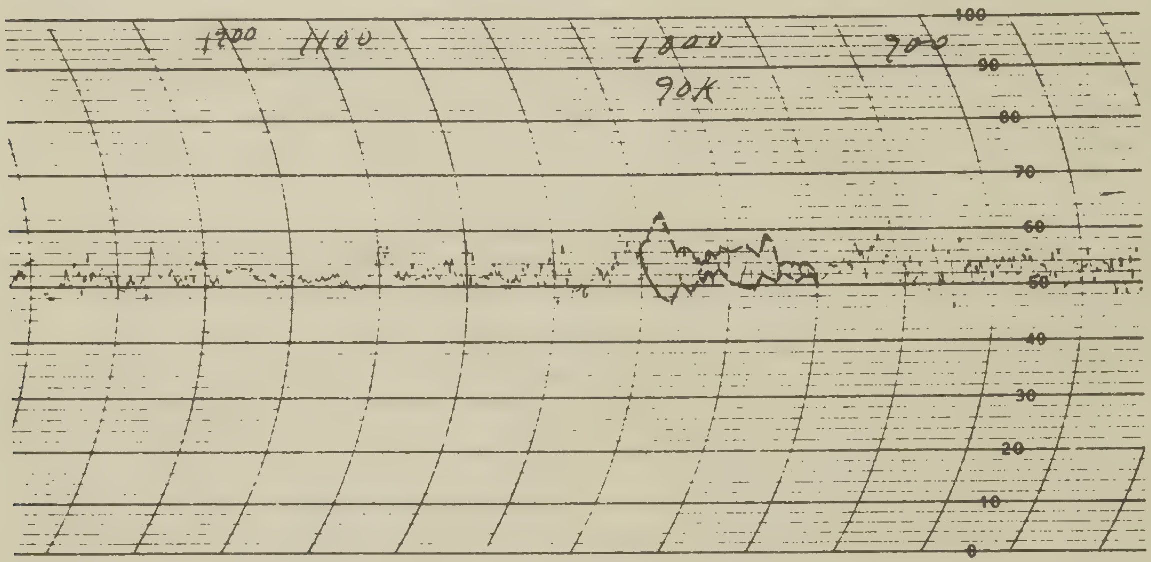

Fig. 3.13.2. Accelerometer trace with drafted line defining *turbulence index.*

One case of convection-free turbulence frequently encountered in nature is found in a ground layer composed of a heterogeneous fluid with vertical gradients of both the turbulence and potential temperature. An airplane flying through this medium will receive innumerable individual accelerations and temperature variations. These variations are the elements effective in the transport of properties and a correlation would be found to exist between them, if sufficiently fast recording elements were available. However, when a correlation is computed between averages of the roughness and the temperature variations, the coefficient will be zero if the averages are made over distances long relative to the gust sizes.

The effect of initiating autoconvective motions to the stream by applying heat to the lower surface is to add a longer enduring interval of increased turbulence to the existing random sequence of turbulent gusts. The rising parcels of air will have temperatures higher than their environment, and if averages are taken over time intervals nearly equal to the time of passage of the plane through a convective bubble or cell then the correlation coefficient approaches unity. The averaging interval used will affect the value of the correlation yielded since increasingly longer intervals lessen the effect of the shorter enduring turbulent and convective motions.

The following demonstration is given to show the sensitivity of the temperature-turbulence index correlation coefficient to intensity of convection and its relative insensitivity to frequency of occurrence of convective cells. From the definition of the correlation coefficient,

$$r = \sqrt{1 - (S_y/\sigma_y)^2} \qquad (1)$$

where S_y is the square root of the squared deviations from a least-squares line and σ_y is the standard deviation from the mean. It is apparent that for purely turbulent flow

$$S_y = \sigma_y \tag{2}$$

and therefore $r = 0$.

If but a single convective parcel which is warmer and rougher than the surrounding air is initiated in the stream, it is obvious that the value of σ_y is greatly increased by the addition of an observation representing this parcel to the observations representing the turbulent surrounding air. S_y remains nearly the same, so that the value of r is greatly increased. If, however, more convective cells are initiated in the turbulent stream, the values of both S_y and σ_y will increase slightly more, producing a minor change in the value of r representing a single convective parcel. Thus it is concluded that the correlation coefficient is relatively insensitive to the frequency of occurrence of convecting parcels.

When the effect of the intensity of convection is considered, it is seen that the correlation coefficient is highly sensitive to the intensity of the convection relative to the intensity of the turbulence. The intensity of convection may be defined here as the square root of the sum of the squares of the differences of the mean temperatures and mean turbulence indices representing turbulence and convection parcels, *i.e.*, $\sqrt{(\overline{TI}_c - \overline{TI}_t)^2 + (\overline{T}_c - \overline{T}_t)^2}$. This sensitivity may be demonstrated by noting that the warmer and rougher a convecting parcel is, relative to the surrounding air, the greater the value of σ_y will be. The value of S_y will not increase appreciably with an increase in intensity. Thus the value of r will depend primarily on σ_y and it will increase as the intensity of the convection increases.

If convective motions are initiated in a very turbulent air stream, there will be only a slight increase in the σ_y, while there may be a slight decrease in the value of S_y. Thus in the case of convection and turbulence of the same order of magnitude, the correlation coefficient will have a small positive value.

Another case to be discussed is the forced convection in the vicinity of a rough surface which is heated or cooled. In this region a gradient of both temperature and turbulence will exist. As in the second case no correlation will exist for a properly long averaging interval if no gusts come directly from the surface, or no convective currents are present. If, however, lines of trees or hills deflect a stream of heated air up into the path of the sounding aircraft, a prolonged interval of rougher heated air will be experienced. This will result in an increase in the correlation coefficient.

3.13.2. OBSERVED CORRELATION COEFFICIENTS

The data for the first two cases discussed, 3 February 1950 and 5 September 1950, were obtained while collecting observations for other problems. They are presented here because they represent ideal cases of the presence of convection within the turbulent ground layer. It is unfortunate that in these cases relatively few simultaneous pairs of values were available for the computation of the coefficient. Consequently, the coefficients for these days have greater probable error than do the other cases. Observational flights for the four remaining cases were organized specifically for this one problem and consequently large numbers of pairs were obtained during flights extending more than 20 km.

The following convenient form of the correlation expression was used in computing the correlation coefficients.

$$r = \frac{n\sum(xy) - \sum x \sum y}{\sqrt{[n\sum x^2 - (\sum x)^2]\,[n\sum y^2 - (\sum y)^2]}}. \tag{3}$$

CASE 1: Gulf of Maine, 3 February 1950

The 130-km offshore sounding of this set of data showed such a strong relation between turbulence index and mixing ratio that it was noted by inspection. Since convection was made evident by the formation of 3/10 coverage of small cumulus clouds at the top of the ground layer, it was thought that the relation must be associated with the convective activity and might act as a means of recognizing convection when cumulus clouds do not form.

Computations of the correlation coefficients have been carried out for three sets of data: turbulence index and temperature over Portland, Maine; and turbulence index and temperature, and turbulence index and mixing ratio at 42° 35′N, 69° 30′ W over the relatively warm waters of the Gulf of Maine. Since the plane was continually ascending in a helix and gradients existed in the temperature, the mixing ratio, and the turbulence index, changes of these properties with height had to be eliminated before the correlation computation could be performed.

The results of the computations are presented in Table 3.13.1.

Table 3.13.1. Correlation coefficients, 3 February 1950.

Portland, Maine		Gulf of Maine (42°35′N, 69°30′W)			
Height (m)	Temp. Turb. index	Height (m)	Temp. Turb. index	Height (m)	Mixing ratio Turb. index
120– 610	+0.6	210– 610	0.0	150– 300	0.1
640–1220	+0.3	640–1220	+0.7	300– 600	0.3
1250–1520	−0.2	1250–1610	−0.5	600– 900	0.6
1580–1830	−0.3			900–1200	0.5
				1200–1500	0.4

On this day a cold air mass was moving from the northwest over the warmer waters of the Gulf of Maine. No cumulus clouds were present over Portland but up to 3/10 were developing in the second sounding area 130 km downwind from Portland. The turbulence over the land was unusually great, frequently imparting vertical accelerations of 300 cm/sec^2 to the two-engined airplane. The general turbulence moderated considerably over the water, although a few accelerations still attained 300 cm/sec^2. These strong accelerations were less frequent and longer enduring than those encountered over land.

The Gulf sounding shows large values of the correlation and a variation with height which is interpreted as the effect of convection. The zero correlation is interpreted to mean that any convective motion present at the lowest level was too weak and underdeveloped to be detected by the present method, but autoconvective currents were well developed at the higher level. The negative coefficient indicates that the air parcels were decelerating (cooler) as they penetrated the inversion at the top of the ground layer. The mixing ratio correlation does not, of course, change sign at the inversion as high values of the mixing ratio are still associated with the rougher air.

Since the Portland sounding yields but a single high value at the lowest level and no trace of cumulus clouds existed in the area, it is concluded that free convection was absent or very weak. The high value (0.6) found in the first 600 m is thought to be evidence of forced convection discussed in the previous section.

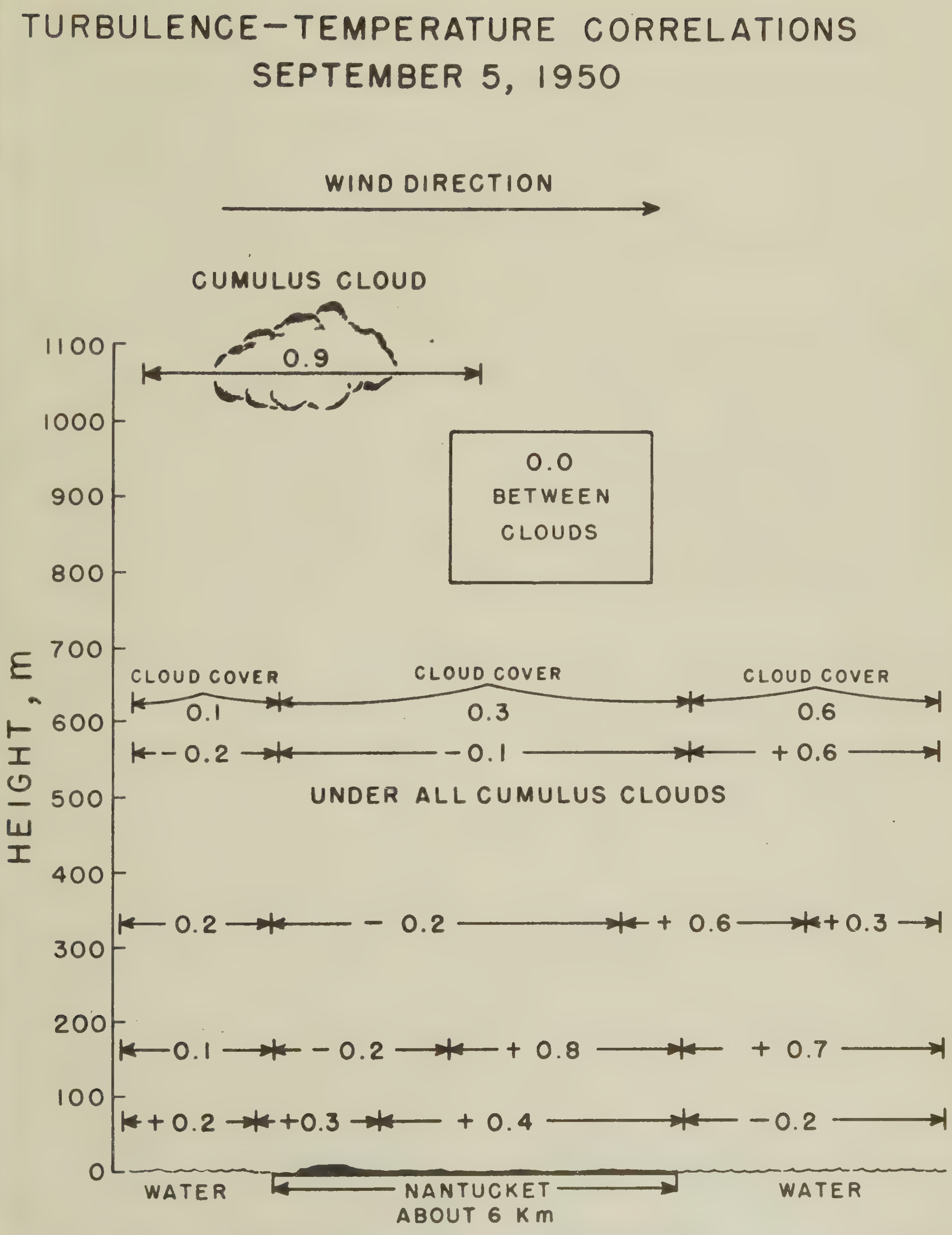
TURBULENCE—TEMPERATURE CORRELATIONS
SEPTEMBER 5, 1950
WIND DIRECTION
CUMULUS CLOUD
0.9
0.0 BETWEEN CLOUDS
CLOUD COVER 0.1
CLOUD COVER 0.3
CLOUD COVER 0.6
-0.2
-0.1
+0.6
UNDER ALL CUMULUS CLOUDS
0.2
-0.2
+0.6
+0.3
0.1
-0.2
+0.8
+0.7
+0.2
+0.3
+0.4
-0.2
HEIGHT, m
1100
1000
900
800
700
600
500
400
300
200
100
0
WATER
NANTUCKET
ABOUT 6 Km
WATER

Fig. 3.13.3. Cross section of atmosphere over Nantucket Island showing correlation coefficients between temperature and turbulence index.

CASE 2: Nantucket Island, 5 September 1950

On this day a cold air mass swept out from land over the warm waters of Nantucket Sound, over the solar-heated island of Nantucket and out over the cooler sea. Over Nantucket Sound 1/10 (measured) cumulus clouds had formed, over the island 3/10, while immediately to leeward 6/10 cumulus were forming. Four long horizontal runs were made upwind and downwind over the island at different altitudes. Several short runs were made in selected regions. The correlations computed from these flights are presented on a cross section, Fig. 3.13.3, of the atmosphere over Nantucket. Values of the correlation are plotted at the appropriate height with double headed arrows used to indicate the distance over which the data were collected for the computation.

The great increase in the value of the coefficient as the air is modified and heated by the island is coincident with the increase in the activity of convection. This is interpreted as confirmation of the proposition that the presence of convection in a turbulent stream can be detected by means of the correlation coefficient.

One short run was made above the ground layer through a cloud and the air immediately surrounding it. The correlation coefficient was found to be +0.9 in this case of unquestioned convection. Several short runs made between clouds yielded coefficients of 0.0. The existence of a correlation of 0.9 in the "cloud layer" immediately above a layer in which correlations of only ±0.2 existed emphasizes the role of condensation in accelerating convection. The increase in temperature due to the condensation of water vapor combined with its accompanying increase in buoyant force greatly increases the value of the correlation coefficient. In contrast, convection motions in the turbulent ground layer have as their source of energy only the relatively small temperature differences resulting from contact with a heated surface. The mixing of the turbulent air rapidly diminishes the temperature difference between a parcel of air originally near the heated surface and the surrounding air. Thus the difference grows smaller as the parcel moves through the air. In the "cloud layer," however, the temperature difference between the cloud and the surrounding air continually increases until a stable layer is reached which halts the cloud's ascent.

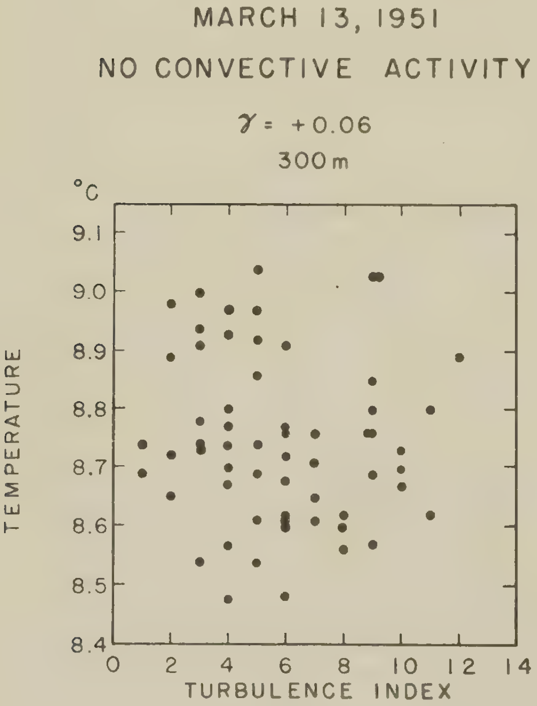

Fig. 3.13.4. Plot of temperatures and turbulence indices observed at 300 m, 13 March 1951, a day with little or no convective activity. Correlation coefficient equals 0.06.

Over the island and downwind at the higher levels the value of the coefficient rises to the significant values 0.6 to 0.8. It is in this region that convection occurs and the cumulus clouds above the level of the airplane attain 6/10 coverage. The drop from a value of 0.4 to −0.2 at low levels leeward of the island coincides with the change from a heat source to a heat sink at the surface.

CASE 3: Middleboro-Fall River, Massachusetts, 13 March 1951

Observations were made on this day as convection was considered to be weak or absent. A 10/10 coverage of stratus with 600 m base existed, cutting off the solar radiation from the ground. The

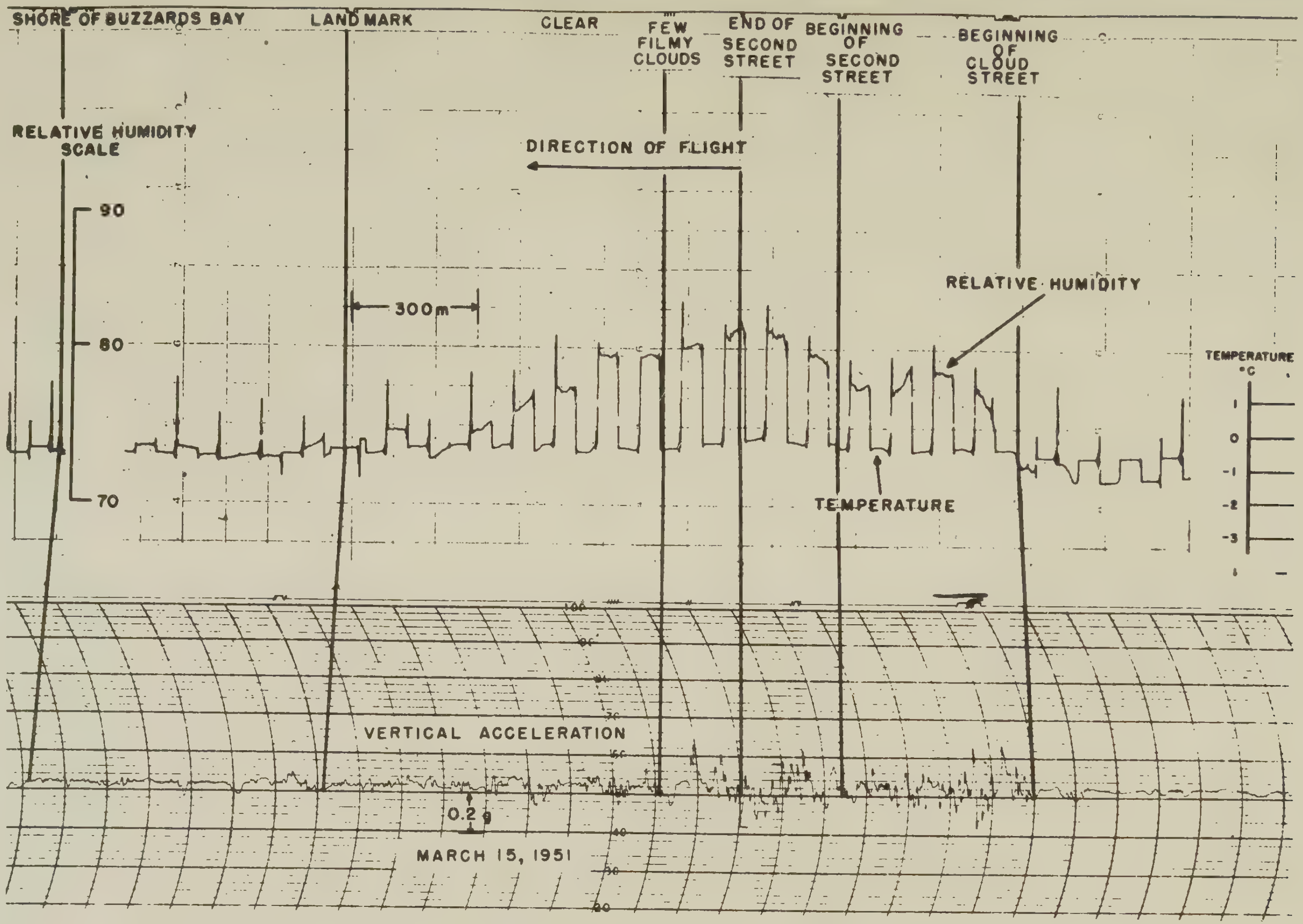

Fig. 3.13.5. Flight records obtained during horizontal run under "cloud street" at 600-m altitude.

following table gives the computed values of the correlation coefficients. Sixty to eighty pairs of values were used in the computation. The probable error of a correlation coefficient determination is thus about ±0.1. Correlations were obtained at various altitudes with different averaging intervals. The averaging interval is expressed in both time and distance traveled by the airplane.

Table 3.13.2. Correlation coefficients between temperature and turbulence index. Middleboro-Fall River, Mass., 13 March 1951

Altitude (m)	Averaging interval			
	300 10	600 20	1200 40	2400 (m) 80 (sec)
150	0.22	0.39	0.44	0.47
300	0.06	−0.10	−0.13	−0.14
550	0.24	0.33	0.48	0.34

The low values entered in the 10-sec column agree with the expectation that low values would be associated with the absence of convection. The higher values found for the longer intervals may be associated with weak large-scale convection. A plot of the values of temperature and turbulence index, Fig. 3.13.4, shows the random distribution characteristic of turbulence without convection.

CASE 4: Cape Cod, Massachusetts, 15 March 1951

The one short run presented here was made under one of the lines of cumulus clouds called "cloud streets" by the glider pilots who travel many miles with the lift from their updrafts. This particular line of cumulus originated during the passage of the air over the Elizabeth Islands which form a chain lying roughly parallel to the wind direction. The combination of slight turbulence, instability, heating, and frictional drag by the islands was suitable to produce an enduring convection pattern. The "cloud street" extended for more than 20 km. The horizontal run was made at 600 m perpendicularly under the line of clouds. Figure 3.13.5 presents the unreduced records of the psychrograph and accelerometer. The increase in turbulence under the clouds was phenomenal. Accelerations in the clear air ranged around 50 cm/sec² while under the "street," accelerations greater than 200 cm/sec² were recorded.

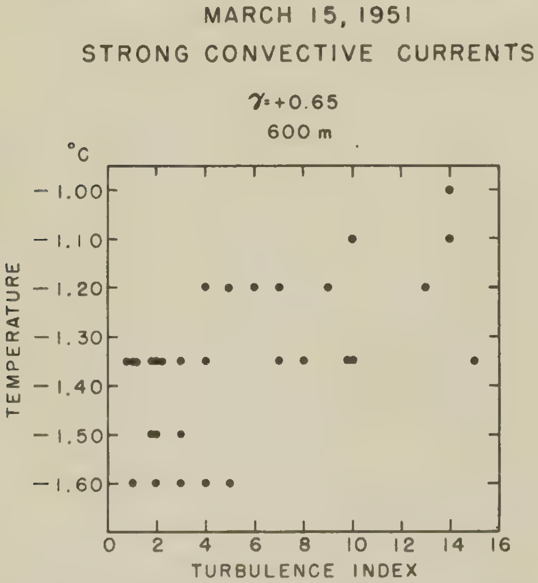

Fig. 3.13.6. Plot of temperatures and turbulence indices observed at 600 m, 15 March 1951.

The correlation coefficient computed from the twenty pairs of values obtained during the 6-km run was found to be +0.65. From this case, the only one in which it can be stated positively that a convection pattern existed in the ground layer, it is demonstrated again that the correlation coefficient is capable of detecting the presence of convection in a turbulent stream.

Figure 3.15.6 shows how the random distribution of points characteristic of turbulence (Fig. 3.13.4) changes when convection is present in the stream.

CASE 5: **Duxbury-Middleboro, Massachusetts, 4 April 1951**

Heating of the land in this region initiated cumulus cloud formation a few hours after sunrise. The amount increased rapidly until at noon, the approximate time of the flights, a general overcast of strato-cumulus had formed. Not all of this cloud cover can be attributed to convective activity as strong convergence was operative in the atmosphere in connection with a closed low aloft. In the overcast there were large broken areas with 6/10 to 9/10 coverage of cumulus clouds. The lowest 150 m of air had a strongly superadiabatic lapse rate, while the next 1000 m was slightly stable (+1°C increase in potential temperature in 1200 m). As a result of this combination of instability and stability, the turbulence was very intense in the lowest level but died off rapidly with height in the stable region.

Correlations have been determined primarily from the data obtained in the broken areas as the temperature deviations under the thick overcast were small. Table 3.13.3 has been prepared to present the correlations obtained at the various altitudes with different averaging intervals.

Table 3.13.3. Correlation coefficients between temperature and turbulence index. Duxbury-Middleboro, Mass., 4 April 1951

Altitude (m)	Averaging interval					
	150 5	300 10	600 20	1200 40	2400 80	3600 (m) 120 (sec)
150	0.53	0.20	0.22	0.29	0.39	....
300	....	0.47	0.47	0.51	0.44	....
800	....	0.44	0.49	0.41	0.66	....
1350	....	−0.22	−0.30	−0.40	−0.80	−0.95

The routine of data reduction was changed to make 5-sec averages from the 150-m level records. This was done as it was obvious from inspection that a short-period relation existed that was completely lost by the usual computation of 10-sec averages. No other level showed evidence of a 5-sec relation. The high coefficient value of 0.53 is associated with the proximity of the heated surface. It is considered another example of forced convection produced by the roughness of the underlying surface.

The coefficients determined for the other heights show that higher values are obtained from the longer averaging intervals. The 10-sec interval and the 120-sec interval values of the temperature and the turbulence index for the 1350-m level have been plotted in Fig. 3.13.7 to show the transformation from the nearly random distribution to a linear relation with very little scatter of the observed points.

A steady shift occurs with height of the maximum coefficient value to longer intervals, until, at the 1350-m level and 3600-m interval, the large value of −0.95 is attained. This height-interval relation suggests a structure of convective parcels or cells that is small near the ground and expands with height so that at the top of the ground layer it is many times broader than it is high. Discussion of the structure of convection is beyond the scope of this paper, but it is suggested that the correlation coefficient can serve as a tool in its study.

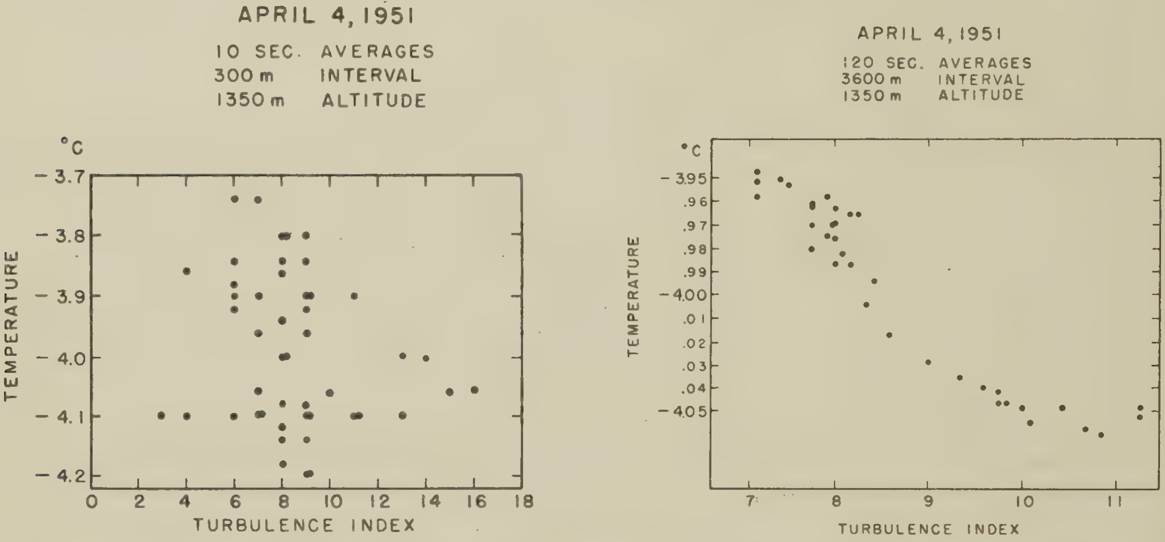

Fig. 3.13.7. Plots of 10-sec and 120-sec averages of temperature and turbulence index observed 4 April 1951.

CASE 6: Ames-Bridgewater, Massachusetts, 17 April 1951

An unstable showery air mass was moving southeast over the region from Ontario on this day. The 8/10 coverage of cumulus and cumulonimbus was produced by the heating of the air as it moved southward over the warmer land. The air was very turbulent and varied little from near the ground to the cloud base at 1800 m. The following table gives the correlation coefficients found on this day.

Table 3.13.4. Correlation coefficients between temperature and turbulence index. Ames-Bridgewater, Mass., 17 April 1951

Altitude (m)	Averaging interval			
	300 10	600 20	1200 40	2400 (m) 80 (sec)
150	0.22	0.20	0.03	....
300	0.18	0.12	−0.03	....
750	0.22	−0.05	0.03	....
1800	0.05	0.09	0.20	0.28

The exceedingly low values of the correlation coefficients on this day with marked cumulus formation and heating of the air from below can be explained in two opposing ways. One explanation is that the correlation coefficient is incapable of detecting the presence of convection in a highly turbulent stream, although it can recognize its presence in a nonturbulent or moderately turbulent stream. The other explanation is that whenever the turbulence exceeds a certain value the warmer parcels of air are diffused throughout the air mass before their buoyancy forces can accelerate them and thus produce free convection. The turbulence alone is not the controlling factor, as the intensity of the heat source also has a measure of control. However, with extreme turbulence the transport of heat is great and a large density difference between the top and bottom of the air column cannot develop, thus eliminating one of the requirements for initiation of convection.

From the success of the correlation coefficient in detecting convection in the preceding cases, it is concluded that little or no convection was occurring in the ground layer on this day. Further it is concluded that the vigorous convection showers occurring in the "cloud layer" were possible because the lower degrees of turbulence in this layer could not transport the huge amount of heat arriving from below and allowed the development of the necessary density differences.

3.13.3. SUMMARY

It is concluded that the correlation coefficient existing between temperature and turbulence index is capable of detecting the presence of free convection in a turbulent stream. This conclusion is based on the high values obtained in ground layers in which convection was known to exist, such as occurred on 5 September 1950, 15 March 1951, and 4 April 1951. Conversely, small values occurred on 13 March 1951, a day with little or no convection activity. The observations bear out the demonstration that the coefficient is dependent primarily on the intensity of convection.

The correlation coefficient should not be used alone as a test for convection, but should be used in conjunction with other means of analysis. Analysis of the processes operating in an air mass and their relative importance may be aided greatly by the computation of the temperature-turbulence index correlation coefficient.

Applying the correlation test to a highly turbulent air stream it is found that the flow does not break down into convective motions even though the air mass is in unstable thermal equilibrium and convection is active in the overlying layer.

The sensitivity of the correlation coefficient to the interval over which the values are averaged makes it a valuable tool for the study of the structure of convective parcels or cells.

3.13.4. ACKNOWLEDGMENTS

The major part of the airplane observing necessary for the completion of this paper was done by Kenneth McCasland. Joanne S. Malkus obtained the observations over Nantucket Island on 5 September 1950.

3.13.5. DISCUSSION edited by O. G. Sutton

MR. A. R. KASSANDER: I would like to emphasize to the group that Mr. Bunker kept his thermistors orientated with the wind in the investigations that he conducted, so the principal objection to the thermistor certainly doesn't apply in the case of his data.

MR. J. E. MCDONALD: I would like to ask Mr. Bunker about the possibility of measuring fine-grain turbulence in clouds. The general problem of turbulence within clouds is almost certain to be quite different because of the distributive heat sources that exist there. For cloud physics it will be an important question, and presumably cloud turbulence measurements might be made from an airplane. I wonder if you have any ideas about the future possibility of getting at this microturbulence?

MR. A. F. BUNKER: I can't see how you would do it from an airplane, simply because the airplane does move so fast through the air. You would have to develop an entirely new instrument with faster response, so for the time being it is impossible to do it from an airplane. You will have to use balloons or helicopters for the purpose.

Contribution No. 574

A later test by SCHELL [1940] of the pressure-ice and temperature-ice relations indicated above, employing the independent data for the 13-year period 1927-1939, showed fair agreement between the computed and actual deviations. However, it was recently suggested by WALKER [1947], from an overall consideration of the stability of the previously derived relationships by Smith and Groissmayr, that these relationships have undergone a marked change. In place of these relationships, Walker suggested that the pressure distribution to the west of Baffin Bay plays an important part in determining the number of bergs that drift southward in Baffin Bay and Davis Strait. These arrive in late spring and early summer in reduced numbers off Newfoundland.

With only Point Barrow pressures at his disposal, Walker correlated the mean monthly October-November values at that station with the berg count off Newfoundland the following spring and early summer. The coefficient of correlation obtained was r = -0.74 (1922-1939). He assumed that lower-than-normal pressure in the general area of northern Alaska must mean a greater-than-normal south-to-north (Point Barrow) pressure gradient, and hence stronger-than-normal west winds all the way to Baffin Bay. These strong winds in turn lead to a greater movement of bergs into the Bay and thence southward along the Labrador coast toward Newfoundland. The interval of four months (December to March) between the end of the pressure season and the beginning of the ice season is a very rough estimate of the time required for the bergs from Baffin Bay to appear off Newfoundland. However, it was recently pointed out by the author [SCHELL, 1948] that the prevailing wind at Point Barrow during October-November is from the northeast rather than from the west. Also a correlation of the October-November Point Barrow pressures with the ice off Newfoundland during the following season, utilizing the data now available for the periods 1940-1949 and 1900-1921 (subsequent to and preceding, respectively, the period 1922-1939 examined by Walker), gave r = 0.19 and 0.26, respectively. The apparent overall association during the entire period of 50 years, including the 21 available to Walker, was practically nil (r = -0.09, 1900-1949, n = 50).

Stability and mutual compensation of the relationships

North Atlantic pressure gradients and temperatures and subsequent ice--In maintaining that the relationships derived by Smith and Groissmayr have undergone a very marked change, Walker did not consider quite the same combination of months as did Smith. What may be more significant, while some relationships were found by Walker to have weakened in their apparent control of the ice, others appear to have strengthened. This raises the question whether in the combinations of relationships used by the earlier investigators there may not have occurred enough mutual compensation to offset the overall change suggested by Walker's work.

As a test of Walker's findings, correlation coefficients were computed using time intervals in better agreement with those employed by Smith and Groissmayr. The greater body of data now available was utilized (Table 1). The correlation between the ice and the preceding October-to-January Bergen-to-Stykkisholm pressure gradient is 0.30 (1880-1949, n = 70) and that between ice and the December-March Belle Isle-to-Ivigtut pressure gradient is 0.53 (1883-1949, n = 67). Breaking up the periods into halves we obtain for the second half of the period, using the Bergen-to-Stykkisholm pressure gradient, r = 0.08 (1915-1949, n = 35) and, using the Belle Isle-to-Ivigtut pressure gradient, r = 0.58 (1917-1949, n = 33). This indicates that, although the relation of the Bergen-to-Stykkisholm pressure gradient with the ice has virtually ceased in recent years, possibly on account of a northerly shift of the Icelandic Low in the northeastern North Atlantic [SCHERHAG, 1936], still there has been no real change in the marked relation of the Belle Isle-to-Ivigtut pressure gradient with the following ice off Newfoundland (see Table 1).

Table 1--Relation of iceberg count off Newfoundland during spring and early summer to the preceding Bergen-Stykkisholm and Belle Isle-to-Ivigtut pressure difference

With Bergen-Stykkisholm pressure difference			With Belle Isle-Ivigtut pressure difference		
Period	n	Coeff., r Oct.-Jan.	Period	n	Coeff., r Dec.-Mar.
1880-1949	70	0.30	1883-1949	67	0.53
1880-1914	35	0.47	1883-1916	34	0.44
1915-1949	35	0.08	1917-1949	33	0.58

Table 2--Relationship of iceberg count off Newfoundland during spring and early summer to the preceding temperatures at St. John's, Bermuda, and Uppsala

Period	n	Coefficient, r		
		St. John's Dec.-Feb.	Bermuda Dec.-Feb.	Uppsala Mar.
1880-1949	70	-0.45	0.32	0.54
1880-1914	35	-0.64	0.42	0.50
1915-1949	35	-0.23	0.24	0.62

A recomputation of Groissmayr's correlation coefficients between ice and the preceding temperatures at St. John's, Bermuda, and Uppsala, based on data for the 70-year period 1880-1949, show (see Table 2) that, while the individual relations of the Bermuda and St. John's temperatures with the following ice have undergone a very marked change from the first half of the period (1880-1914) to its second half (1915-1949), the overall relation would appear to be rather stable. The lesser association of the ice with St. John's and Bermuda temperatures during the period 1915-1949 apparently was to a marked extent compensated by the greater association with Uppsala temperatures of the same period.

Performance of relationships during 1927-1949--From the above examination of the stability of the relationships between iceberg severity off Newfoundland and the pressures and temperatures of the North Atlantic and adjacent areas, it would appear that, while the pressure gradient, Bergen-to-Stykkisholm, has ceased to indicate an inflow of air into the Arctic followed by an outflow along the west sides of Baffin Bay and Davis Strait, the pressure gradient, Belle Isle-to-Ivigtut, continues to reflect the northerly air flow along the Labrador coast, which in turn materially affects the number and speed of bergs that drift southward to Newfoundland waters (see Table 1).

Similarly, the combined preceding temperatures at St. John's, Bermuda, and Uppsala continue as during 1880-1926 to reflect an influence on the iceberg severity off Newfoundland the following late spring and early summer (see Table 2). This correlation is more stable when employing the full interval December-March for all three temperature terms rather than December-February for St. John's and Bermuda, and March for Uppsala as was done initially. This is shown in Table 3.

Table 3--Relationships between the ice off Newfoundland and December-to-March St. John's, Bermuda, and Uppsala temperatures compared with that using December-to-February St. John's and Bermuda, and March Uppsala values

Period	n	Coefficient, r					
		St. John's		Bermuda		Uppsala	
		Dec.-Mar.	Dec.-Feb.	Dec.-Mar.	Dec.-Feb.	Dec.-Feb.	Mar.
1880-1949	70	-0.49	-0.45	0.40	0.32	0.55	0.54
1880-1914	35	-0.60	-0.64	0.41	0.42	0.54	0.50
1915-1949	35	-0.39	-0.23	0.36	0.24	0.58	0.62

As a test of the relationships of the ice with the Belle Isle-to-Ivigtut pressure gradient and St. John's, Bermuda, and Uppsala temperatures indicated above, the values of the ice departure from normal using a scale of zero to 10 for the recent 25-year period 1927-1951 were computed with the aid of the following formula based on data to 1926 inclusive.

$$\Delta\text{Ice (Newfoundland)} = +0.12\Delta \text{ pressure difference (Belle Isle-Ivigtut)} - 0.31\Delta \text{ temperature (St. John's)} + 0.19\Delta \text{ temperature (Bermuda)} + 0.17\Delta \text{ temperature (Uppsala)}$$

Here, Δ refers to deviation from the long-term December-to-March averages which are: Belle Isle-Ivigtut pressure difference, 5.52 mm; St. John's temperature, 25.6° F; Bermuda temperature, 63.2° F; Uppsala temperature, -3.0°C.

The computed values of ice anomaly are shown together with the actual departures in Table 4.

As might be expected from the evidence of marked stability and mutual compensation of the relationship between ice and the December-March temperatures and the Belle Isle-Ivigtut pressure gradient (Tables 1 and 3), there is a marked agreement between the computed and actual anomalies in recent years also (1927-1951) (Table 4). Of the 25 cases involved, disagreement as to sign between the computed and observed deviations occurred in only five years (1929, 1944, 1945, 1946, 1949), and of the 12 cases with a computed deviation in excess of ± 1.0 disagreement as to sign

Table 4--Computed and observed departures (Δ) from the long-term normal (1880-1926) in the iceberg severity off Newfoundland (1927-1951) on scale of 10

Year	Computed	Observed
1927	-0.1	0.0
1928	0.3	0.8
1929	-0.2	4.2
1930	2.0[a]	0.6
1931	-1.8[a]	-2.8
1932	0.5	0.8
1933	-0.1	-1.1
1934	1.4[a]	1.0
1935	0.8	2.7
1936	-2.0[a]	-2.8
1937	0.4	0.6
1938	1.1[a]	1.8
1939	1.1[a]	1.8
1940	-2.7[a]	-4.7
1941	-1.5[a]	-4.7
1942	-2.4[a]	-2.4
1943	0.8	2.4
1944	-0.3	2.0
1945	-0.8	3.9
1946	-0.4	0.1
1947	-1.5[a]	-2.0
1948	0.4	1.1
1949	0.4	-2.1
1950	1.1[a]	0.4
1951	-2.0[a]	-4.7

[a] Values in excess of ± 1.0.

occurred in none, while the overall agreement in terms of the correlation coefficient for the entire 25-year period is r = 0.80.

Discussion

The above study indicates that the general premise about changes in the circulation in the North Atlantic and adjacent areas affecting the following iceberg count off Newfoundland is true. Of the variously derived relations by Smith and Groissmayr, only the October-January Bergen-to-Stykkisholm pressure gradient appears to have ceased to be significant, and we may conclude that changes in this pressure gradient in October-January have not continued to lead to changes in the outflow of cold air the following spring over Baffin Land, perhaps because of the marked alteration in the pressure field in recent decades over the northeastern North Atlantic [SCHERHAG, 1936].

The reason for considering only indications of air circulation by the author and previous investigators in developing the formula for foreshadowing the severity of the iceberg season off Newfoundland is due to the small volume of the currently accumulated measurements of the strength and heat content of the Labrador Current. Similarly, the counts of the iceberg population to the north, which may be expected to figure in the number of bergs appearing off Newfoundland, have been too few so far to allow their possible inclusion in the formula.

In making use of the method given here for foreshadowing the iceberg count off Newfoundland, it appears best for each user of the formula to decide for himself the tolerance or limits most suited for the operation in question. The only requirement in each case is that the foreshadowings yield results that are significantly better than chance.

Because the berg count used in our computations is based on a scale of 10, we may wish to use a tolerance of one unit. It should be borne in mind that the probability of a given foreshadowing verifying by chance varies also with the class interval of the computed deviations. The highlighting above of the five cases of disagreement as to sign between the computed and actual deviation out of a possible 25 (Table 4) was to provide a ready comparison with the figure possible by chance (50 pct). Also because a foreshadowing with an indicated 100 pct chance of success has a special meaning, attention was called to the fact that in the 12 cases out of the 25 when the computed deviation exceeded 1.0 on the scale of 10, each agreed as to sign with the observed deviation. A foreshadowing that the number of bergs will fall below 440 (the average value on the scale of 10) may be of little value for some operations, but the information that anything over that number (and possibly over 1000 as in some years) is not likely to happen may be of great value for other operations.

In the original investigation by SMITH [1931], the months with a higher degree of correlation as shown by the coefficient, r, were given twice the weight of the months with smaller values of r. Presumably this was done because a derivation of regression equation giving each coefficient its full weight would imply an undue exactness of the relationships.

It is equally true, however, that where the months in question adjoin each other, the general fluctuation of the relation with time often involves an increase in the association of the months with smaller values of r and decrease for the months with larger values of r. Accordingly, we may desire to treat all months with a significant degree of correlation, but whose coefficients may differ somewhat among themselves, as of equal weight.

Thus it was found that the relation of the unweighted December-to-March monthly data of the Belle Isle-to-Ivigtut pressure gradient with the ice appeared actually closer than the relation of the weighted ones, the obtained values of r (1883-1949, n = 67) being, r = 0.53 and r = 0.47 respectively.

Data and acknowledgments

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I am also indebted to Joseph G. Galway for carrying out the detailed computations of this study.

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Contribution No. 576

2.2. THE PRESENT POSITION OF THE STUDY OF EXCHANGE ACROSS THE OCEAN-ATMOSPHERE INTERFACE

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International Symposium on Atmospheric Turbulence in the Boundary Layer
4 – 8 June, 1951
GEOPHYSICAL RESEARCH PAPERS NO. 19

ABSTRACT

The various measurements yielding estimates of the interfacial stress (total horizontal stress at the water surface) are discussed at some length; the results are so conflicting that at no wind speed is the resistance coefficient known confidently within half its value, and a new method for measuring the stress is needed. Brief comments are made on other topics: the nature and resolution of the interfacial stress and of the transmission of mechanical power from wind to waves and currents, heat flux by radiation, the lack of a satisfactory method for measuring the temperature of the interface, and some recent values for the Kármán constant.

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2.2.1. INTRODUCTION

Atmospheric turbulence in the boundary layer over the ocean-atmosphere interface entails peculiar problems. The question is still open as to how directly applicable the empirical results from flow over solid surfaces are.

Boundary-layer turbulence is intimately associated with transfers across the boundary, and this paper reviews the transfer, across the ocean-atmosphere interface, of (1) momentum, (2) mechanical energy, and (3) heat and water. No attempt is made to summarize and evaluate all the pertinent contributions. The purpose of the symposium is better served by calling attention to certain recent advances and by emphasizing some of the outstanding problems.

Other topics are included in Charnock's [2] stimulating review of energy transfer between atmosphere and ocean.

2.2.2. MOMENTUM

Estimates of the total horizontal interfacial stress (interfacial momentum flux per unit area), τ_0, rest largely on indirect evidence. One part of the evidence is that a few observations of vertical distribution of mean wind near the interface have been compared with the velocity distribution in long circular pipes so that the interfacial stress could be estimated from the known wall stress in the pipes (see also Sec. 2.2.6.). Most of the evidence up to 1947 could be fitted into an apparently consistent pattern, and the resulting estimates of stress have then been applied to other problems with apparent success.

The stress is often expressed in terms of a resistance coefficient γ^2 (sometimes written κ) defined by

$$\tau_0 = \gamma^2 \rho_a u^2,$$

where ρ_a is air density and u is mean wind speed at a given distance above the interface, for present purposes about 10 m. What were considered good values of the coefficient are shown, for instance, in a curve by Munk [17, Fig. 49], from which the column in Table 2.2.1 was read. The sharp increase at a wind of about 7 m/sec supposedly accompanies a change from aerodynamically smooth sea surface to aerodynamically rough sea surface. Munk makes the excellent suggestion that the abrupt change can be explained in terms of the Kelvin-Helmholtz instability criterion, which shows an ideal interface (with appropriate values of gravity, densities, and surface tension) to be unstable for a velocity difference exceeding 6.6 m/sec; when this critical difference is exceeded, wavelets roughen the surface.

Table 2.2.1. Over-water resistance coefficient, γ^2, as a function of wind speed at about 10 m.

	Munk (1947)	Neumann (1948)	Francis (1951)
1 m/sec	0.0010	0.0090	......
2	.0009	.0064	......
4	.0008	.0045	0.0005
6	.0008	.0037	.0008
8	.0026	.0032	.0010
10	.0026	.0028	.0013
15	.0026	.0023	.0020
20	.0026	.0020	.0026
25	.0026	.0018	.0032

Values of the resistance coefficient are presented as a function of wind speed alone for lack of further information. They are regarded as applicable primarily to ideal conditions consisting of deep water, homogeneous water, homogeneous air, and "equilibrium" state of sea (steady wind with long fetch, no effect of currents). Although sufficient departure from any of the ideal conditions can be expected to affect the resistance coefficient profoundly, there is no reliable quantitative information. In applications the same values have perforce been used regardless of conditions.

In 1947 Roll [30] carried out a pioneer observational program that can well serve as a model for further observations under other conditions. From fixed supports he measured simultaneously the vertical distribution of wind relative to the interface, the vertical distributions of temperature and wet-bulb temperature, and the characteristics of the waves. The wind distributions all indicate a smooth sea surface, although the relative wind at 2 m ranged from 2 to 12 m/sec. Roll's observations were made on a tidal flat, but nevertheless the discrepancy with Munk's results is not easily resolved.

A more direct method is to calculate the interfacial stress from the observed steady-state interfacial slope due to wind. "Wind slope" is the English term proposed for this phenomenon. The stress is related to s, the slope component in the wind direction, to depth h, to gravity g, and to water density ρ_w by

$$\lambda\tau_0 = \rho_w g h s, \qquad \lambda \geq 1,$$

a consequence of the assumption that the horizontal mass flux integrated vertically from interface to bottom is zero. In homogeneous water the factor λ can be expected to be close to unity, the theoretical value for deep, homogeneous water. If either the eddy viscosity increases downward or there is stratification, however, λ has no upper limit.

The wind-slope method of calculating stress is the oldest, having been introduced in 1905 by Ekman [8]. The method has recently been re-examined by Neumann [18], who concludes, using Baltic Sea data assembled by Palmén [22; 23] and Palmén and Laurila [24] with $\lambda = 1$ and data assembled by Hellström [13], that

$$\gamma^2 = 9.0 \times 10^{-3}\left(\frac{1\ \mathrm{m/sec}}{u}\right)^{1/2}$$

for winds from 1 to 40 m/sec. Values from this formula are included in Table 2.2.1 for comparison with Munk's. (A similar comparison has been made by Neumann [19, p. 157]). For light winds Neumann's values are five to nine times Munk's values, and even for stronger winds they differ by as much as 40 percent. Neumann's results are subject to some uncertainty in choice of values for the factor λ and the depth h; furthermore most winds were converted from Beaufort estimates. One of the discussions of the factor λ is that by Palmén [25].

Hela [12], in a study of wind slope during a Baltic Sea storm in November 1934, concludes that for winds from 10 to 25 m/sec the resistance coefficient is about 0.0019.

Measurements of wind slope on Lough Neagh seem to indicate that the coefficient is 0.0013 for all winds up to 10 m/sec (G. E. R. Deacon [6]). Final results are awaited.

Hellström [13] and Francis [10] have used the wind-slope method in wind tunnels. The depth of water in Hellström's tunnel was variable up to 4 cm. According to his wind-stress magnitudes, which he says "for practical purposes . . . are of no value," the resistance coefficient is proportional to the wind speed 20 cm above the interface and increases linearly with water depth. Francis's water depth was 15 cm; the resistance coefficient is again nearly proportional to wind speed at 10 cm and varies considerably with other conditions. For winds extrapolated to an elevation of 10 m, where they range from 4 to 26 m/sec, Francis obtains the "very tentative" relationship that

$$\gamma^2 = 0.13 \times 10^{-3} \frac{u}{1 \text{ m/sec}},$$

which yields the values in the last column of Table 2.2.1. The wind-tunnel results cannot be applied to natural conditions with assurance until more is known about how well the flow of air and water in the tunnel reproduces natural conditions.

Another relatively direct method, first used by Richardson [29] for determining the stress on a land surface, is based on the departure from geostrophic wind in the friction layer, the departure in momentum of a vertical column of unit horizontal cross-sectional area being equated to the interfacial stress. This method has supplied the values in Table 2.2.2. These values (except the first) are much smaller than any corresponding values in Table 2.2.1. Durst's would seem to be proportional to the wind speed, and he gives a proportionality factor such that

$$\gamma^2 = 0.07 \times 10^{-3} \frac{u}{1 \text{ m/sec}}.$$

Table 2.2.2. Over-water resistance coefficient from geostrophic departure.

Author	Average wind at about 10 m	γ^2
Rossby and Montgomery (1935)[32, p. 14]	...	0.0013
Sutcliffe (1936)[36]	7 m/sec	.0004
Durst (1949)[7]	2.7	.00023
	6.7	.00042
	9.8	.00075

It is seen that the two relatively direct methods disagree: a steady decrease with increasing wind is found from wind slope (Neumann), an increase is found from geostrophic departure (Durst); the best agreement is at 10 m/sec, where Neumann's value is four times Durst's. The indirect evidence indicated a discontinuous increase at about 7 m/sec (Munk). The present evidence is so conflicting that at no wind speed is the resistance coefficient known confidently within half its value.

A new, direct method for measuring the interfacial stress is needed. Can a technique be developed for direct measurement of the eddy stress, $-\rho\,[w'u']_{\text{Av}}$, a short distance from the interface, the instrument being mounted on an airplane or submarine? As interfacial stress is certainly not simply a function of wind speed at a fixed elevation, a technique is needed that can be applied under diverse conditions.

The nature of the interfacial stress can hardly be other than complicated. As Neumann [19] warns, it is still hard to tell how well conditions in the air above the sea surface agree with conditions in flow over a solid surface, either smooth or rough, and estimating the stress merely from vertical distribution of wind is very uncertain. Even when the mean (particle) velocity of the interface has been eliminated by being subtracted from all velocities, a complicated motion of the interface remains: for each type of wave present, the orbital motion of material points and the translational motion of the wave form. Neumann [20; 21] has proposed that the total interfacial stress is composed of three (or more) parts, none generally negligible: the viscous drag, the form drag of the dominant waves, which are only somewhat slower than the wind, and the form drag of the slowly moving wavelets. Both Munk and Neumann [19, p. 163] are of the opinion that the last mechanism dominates in moderate and strong winds.

2.2.3. MECHANICAL ENERGY

The transmission of mechanical power from air to water has been studied as the source of energy for waves. Jeffreys [14; 15] took into account only the power from the vertical component of interfacial stress, this component being expressed in terms of an empirical number, the exposure coefficient or sheltering coefficient. This number has been redetermined by Sverdrup and Munk [38]. These authors improve the theory by taking also into account the power transmitted by the horizontal component of stress, but they do so by assuming the total horizontal interfacial stress, regarded as constant over the wavy interface, to act everywhere at the horizontal component of particle velocity. Neumann [20] neglects the vertical component of stress and takes the unit-area wave-generating power equal to the product of total horizontal stress and wave speed. Schaaf and Sauer [33] neglect the stress normal to the wave surface and take the unit-area power equal to the product of tangential stress, which is a function of position on the wave, and tangential component of particle velocity at the interface.

There is seen to be no agreement about the essential mechanism responsible for mechanical power transmission across the interface.

Power from the vertical component of stress must all go into energy of waves and turbulence, but the fact should not be forgotten that power from the horizontal component is also the source of kinetic energy of currents and potential energy of wind slope. If the horizontal stress has three parts, the power it delivers has three parts: viscous stress times horizontal particle speed, form stress of wavelets times wavelet speed and form stress of waves times wave speed. How much of the total power is available for waves?

2.2.4. HEAT AND WATER

A rational approach to heat transfer and evaporation awaits a promising solution of the problems discussed above. This section is limited to parts of the subject.

All the transfer phenomena are influenced by the vertical temperature distribution, which, in the layer from the interface up to an elevation of several hundred meters, is much better known owing to airplane soundings reported by Craig [3; 4] and Emmons [9].

Heat is transferred between ocean and adjacent air partly by radiation. The net radiational heat flux from the lowest meter or so of air has been discussed by Panofsky [26], E. L. Deacon [5], and Goody and Robinson [11, Sec. 4.4].

A method is needed for measuring the temperature of the interface. Roll [31] has shown that the interfacial temperature can differ systematically from the measured temperature of the water near the interface.

2.2.5. OCEANIC TURBULENCE

Transfer across the interface is associated not only with atmospheric turbulence in the superjacent boundary layer but also with oceanic turbulence in the subjacent boundary layer. In the oceanic layer, turbulence and the distributions of velocity and temperature remain almost completely unstudied. Probably there is interaction between atmospheric and oceanic turbulence, so that they could profitably be studied together.

Along with the counterpart of atmospheric turbulence, the counterpart of oceanic waves, namely, wave motion in the air, has been neglected in studies of the interface. Actually, how to separate the fluctuations, not only near this interface but also in stable layers within the atmosphere and ocean, into wave motion and turbulence remains a puzzle.

2.2.6. RELATION TO STUDIES ON LAND AND IN LABORATORY

Although atmospheric turbulence above the ocean-atmosphere interface entails peculiar problems, it shares others with turbulence next to land and artificial surfaces. Two such problems form the subject of this section.

At an aerodynamically smooth surface in turbulent air, a laminar sublayer acts as a resistance to the flow of momentum, heat, and aqueous vapor to the surface. At a hydrodynamically rough surface, this form of resistance is small or absent as far as the flow of momentum is concerned, because momentum is transferred by normal as well as tangential stress. However, nothing analogous to normal stress is available for the transfer of heat and vapor, so physical reasoning indicates that the laminar layer must resist the flow of heat and vapor even at a rough surface. There are, however, two opinions, one that the laminar layer offers significant resistance, the other (*e.g.*, Sverdrup [37], Calder [1, p. 161]) that the flows of heat and vapor are exactly similar to that of momentum.

One of the most reliable and useful relations regarding boundary-layer turbulence is the logarithmic law that next to a large plane solid surface, at distances z neither too small nor too large,

$$\left(\frac{\tau_0}{\rho}\right)^{-\frac{1}{2}} \frac{\partial u}{\partial \ln (z/z_0)} = \frac{\partial (u/u_*)}{\partial \ln (z/z_0)} = \frac{1}{\kappa}.$$

The number κ is often called the *Kármán constant.* Many authors treat it as a well determined constant with the value 0.40. This value is uncertain by at least 12 percent. A value of the same order of magnitude is obtained from measurements of ground stress by Sheppard [35] and Pasquill [27], but their measurements are neither representative enough nor extensive enough to provide a reliable determination or a test of constancy. Most determinations are based on Nikuradse's distributions of velocity and pressure in long circular pipes, where precise and representative measurements are possible. The geometry, however, is different; the eddy stress is constant in the appropriate atmospheric layer but in pipes is proportional to distance from axis. Different values for the constant result from different interpretations of the pipe flow, Montgomery [16] obtaining 0.45. Prandtl [28] and Szablewski [39] adopt 0.417. In a welcome investigation that has escaped notice by meteorologists heretofore, Schultz-Grunow [34] found the wall stress in a wind tunnel of rectangular cross section by measuring directly the tangential force on a suspended panel flush with the wall — a laboratory method corresponding to the field method later used by Sheppard and Pasquill. From his measurements of stress and velocity distribution Schultz-Grunow found that the ratio of mixing length to distance from wall is 0.43, and this ratio is identical with the Kármán constant.

2.2.7. ACKNOWLEDGMENT

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2.2.8. SUMMARY OF DISCUSSION prepared by R. B. Montgomery

Mr. Sheppard gave an interesting account of the recent and as yet unpublished English measurements designed to yield the interfacial stress. Mr. Yoshida's communication (not read at the symposium but reproduced below) describes his preliminary conclusions concerning the mechanisms transferring power from wind to waves.

2.2.9. DISCUSSION edited by R. B. Montgomery

MR. P. A. SHEPPARD: I would like to show a few slides in relation to Mr. Montgomery's paper. Like him and like Mr. Priestley, we have been very concerned to get a more adequate value of this fundamental meteorological quantity, the drag of the ocean's surface, and we have undertaken two expeditions to get it. I may say we have failed, at any rate in our essential purpose. I hope to say something about this on Thursday in a discussion on momentum transfer but would refer here briefly to some results on wind profiles and drag obtained from the expedition with the National Institute of Oceanography over Lough Neagh in Northern Ireland.

[Slides were then shown of the equipment and of the observed vertical distributions of wind. One feature of these distributions was a departure from the expected logarithmic form, a kink appearing characteristically somewhere between 1 m and 2 m. This work is summarized in Section 3 of Mr. Sheppard's "Effects of turbulent flow — eddy fluxes," in these proceedings.]

I think this work shows the inadequacy of this approach and gives us further reason for going directly to the $\overline{u'w'}$ measure in order to get the drag coefficient and momentum transfer. I do, however, wish to stress this point: that the work on Lough Neagh shows the tremendous effect of stability; to talk about a drag coefficient of the sea surface may, in fact, be misleading without taking the stability into account.

MR. W. H. MUNK: Some measurements by members of the Department of Engineering of the University of California also reveal the presence of a kink, which in spite of attempts at smoothing could not be eliminated.

MR. G. B. SCHUBAUER: I fail to understand, Mr. Sheppard, how you determine the drag coefficient from the profile.

MR. P. A. SHEPPARD: You plot the wind speed against the logarithm of the height and take the intercept of this line on the height axis. This intercept is the roughness parameter z_0, from which the drag coefficient c follows,

$$c = \frac{k^2}{(\ln z_R/z_0)^2},$$

where k is von Kármán's constant and z_R is the reference height for the wind.

MR. K. YOSHIDA, Geophysical Institute, Tokyo University (communicated): "The total interfacial stress is composed of three parts: the viscous drag, the form drag of the dominant waves, and the form drag of the wavelets" (Montgomery). I agree with this opinion. As regards this point, I cannot wholly agree with what Mr. Neumann (1950) considered, because effects of the wind stresses on each component wave in the spectrum may be more complicated than he considered. The dominant waves (or significant waves) and the wavelets must be of special importance in these processes. On the other hand, I think that the significant role of breakers, as Neumann remarked, should be stressed and further investigated.

One purpose of my latest work, which is not yet completed, is to try to answer the question: "How much of the total power [of the horizontal stress] is available for waves?" (Montgomery). Without some experimental support, we may be unable to make our conclusions definite.

Energy which the sea receives from winds by the form drag of the wavelets will be transferred partly to the waves and partly to the currents. The origin of such internal transfers may be supposed to be the breaking of wavelets.

Most of the viscous drag goes into the kinetic energy of currents, while most of the form drag goes to waves and currents. Of course, the vertical component of stress must all go into energy of waves. Therefore, it may be that the waves receive their energy from the power of normal pressure, while the current, from those of horizontal viscous stress and normal pressure.

According to these considerations, both the horizontal stress available to waves and that available to currents is, in general, smaller than the total stress ($\gamma^2\rho' W^2$).

At wind velocities less than about 5 to 6 m/sec, the form drag of the wavelets cannot exist. The viscous drag and the form drag of waves, if existent, may be the energy source for waves. The problem of the initial formation of waves may, therefore, have to be attacked in a somewhat different manner from that of Jeffreys.

Contribution No. 578

Vol. XIII, Art. 3.

HYDROGRAPHY OF THE LONG ISLAND AND BLOCK ISLAND SOUNDS

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Reprint fram BULL. BINGHAM OCEANOGR. COLL.

ABSTRACT

Nine cruises in the Long Island and Block Island Sounds[2] in 1946 provide a basis for the description of temperature and salinity distribution in these waters. Data on tides, currents, and freshwater drainage are summarized, and all available information is combined into an analysis and discussion of the physical oceanographic processes that produce the observed distribution of temperature and salinity.

There is a slow southwesterly drift in the coastal waters off southern New England. Part of this water moves into the Sounds, particularly along the bottom, where it is gradually mixed with the products of river drainage; thus the salinity decreases from the open coastal waters toward the innermost ends of the sounds and bays. From these inner waters a compensating surface current moves seaward and joins the general coastwise drift.

L. I. S., being a semi-enclosed body of water, is particularly favorable for quantitative investigation of currents, mixing processes, and the total exchange with adjacent waters. The circulation is mainly controlled by river drainage. Addition of fresh water into the shore zone tends to produce a counterclockwise circulation; however, tidal mixing in areas of little river outflow breaks up the coastal density gradient. The net result appears to be a series of three main eddies—counterclockwise in the east and west ends of L. I. S., with a clockwise eddy between.

The net transport of water from L. I. S. must equal the freshwater drainage, which amounted to 35% of the volume of this body of water in 1946. Observed surface currents indicate a much larger surface transport from L. I. S. into B. I. S., and this is part of the evidence favoring the existence of a two-layered transport system, with water flowing out at the surface and in at the bottom. To maintain the observed salinity in L. I. S., it was necessary for B. I. S. water to be brought in at a mean rate of 7500 m^3/sec, totalling 3.8 times the volume of L. I. S. during 1946. These figures represent the combined effects of lateral eddy diffusion and mass transport.

Although there is a slight seasonal variation in salinity in L. I. S., the salinity distribution tends to be self-regulating. With an increase in river drainage and a decrease in average salinity, there is an increase in the amount of exchange between the two Sounds, so that more B. I. S. water is brought in to counteract the freshening effect. It is suggested that a decrease in salinity increases the slope of the free surface between L. I. S. and the open sea and accelerates both the surface velocity and the compensating bottom current. Quantitative aspects of the theory are briefly examined.

Problems of turbulence are discussed from time to time, and coefficients of lateral eddy diffusivity and vertical eddy conductivity are evaluated. In B. I. S. the eddy coefficients and the observed salinity distribution are used to estimate current velocities.

ACKNOWLEDGMENTS

This survey was made possible by a grant from the Office of Naval Research, to whom grateful acknowledgment is made at this time.

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[2] Hereafter Long Island Sound will be referred to as L. I. S. and Block Island Sound as B. I. S.

A large part of the field work and processing of the data was done by the physical oceanographic staff of the Woods Hole Oceanographic Institution. The writer is particularly indebted to Dean F. Bumpus, Frederick C. Fuglister, Carl Hayes, Garry Metcalf, and to the dozen or more technicians who participated in various aspects of the survey, as well as to the officers and men of the Woods Hole vessels PHYSALIA and ANTON DOHRN.

At various stages in the analysis of data and preparation of the manuscript the work has been discussed with the men listed above and with Columbus O'D. Iselin, Alfred C. Redfield, Henry Stommel, Daniel Merriman, E. F. Thompson, and others. To all of them the writer is grateful for their advice and suggestions.

INTRODUCTION

The following report is based primarily on nine cruises from Woods Hole, Massachusetts to L. I. S. during the period from January 22, 1946 to January 5, 1947. Fig. 1 is a chart of the area covered, with place names that will be referred to and with depth contours taken from U. S. Coast and Geodetic Survey charts. The latter were also used to prepare estimates of the area and volume of L. I. S. and certain subdivisions thereof for use in quantitative analyses to be presented later. Results of these measurements are shown in Table I.

During each cruise, surface bucket temperatures and salinity samples were obtained every 15 minutes en route, together with bathythermograph measurements of the vertical temperature structure. At less frequent intervals, hydrographic stations were occupied, these consisting of temperature and salinity readings at about five depths between surface and bottom. Figs. 2 to 5 show the surface temperature and salinity distribution observed during four of the cruises, and they also serve to illustrate the general cruise pattern. Other cruises, which are not figured but which will be used in later analyses of temperature and salinity distribution, were made on the following dates: Cruise 2, March 17 to 25, 1946; 3, April 29 to May 4; 5, July 11 to 13; 7, October 7 to 13; 9, December 31, 1946 to January 5, 1947.

Also included in the report is a series of bathythermograms and salinity measurements obtained in B. I. S. in 1949. The area covered in the later survey was small, and the observations are therefore of limited interest from a physical oceanographic standpoint. They are included mainly to provide a basis for the physical aspects of the

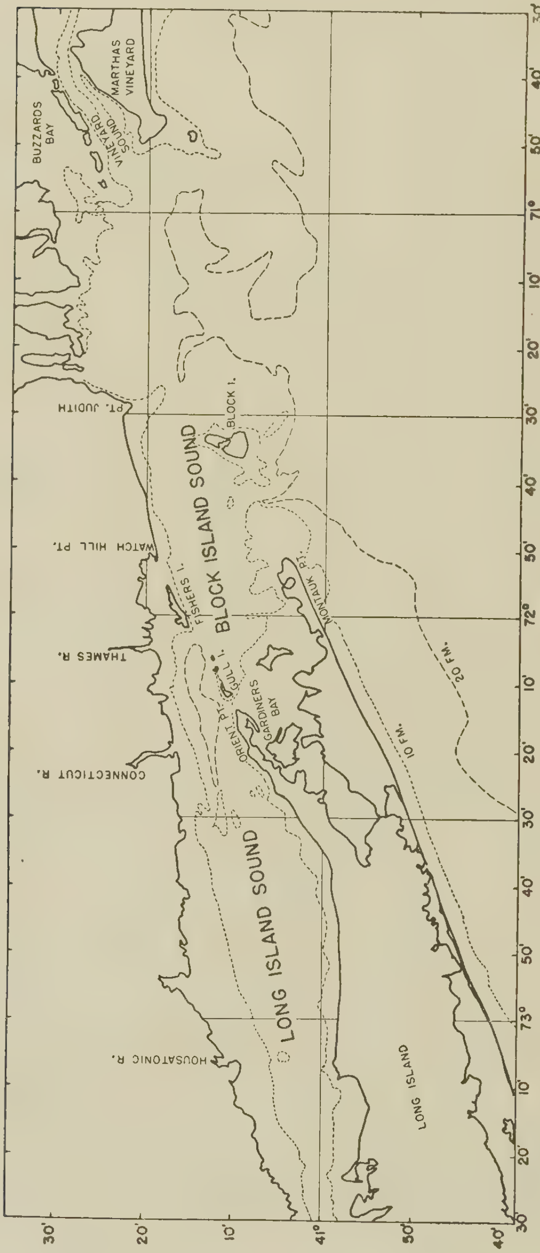
BUZZARDS BAY
VINEYARD SOUND
MARTHAS VINEYARD
PT. JUDITH
BLOCK I.
BLOCK ISLAND SOUND
WATCH HILL PT.
FISHERS I.
MONTAUK PT.
THAMES R.
GULL I.
ORIENT PT.
GARDINERS BAY
20 FM.
10 FM.
CONNECTICUT R.
LONG ISLAND SOUND
HOUSATONIC R.
LONG ISLAND
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Figure 1. Chart of area covered by the survey, showing place names and bathymetric contours.

TABLE I. Area and Volume of L. I. S. The Sound Was Subdivided by Drawing North-south Lines Across the U. S. Coast and Geodetic Survey Charts of the Sound at Intervals of 10 Minutes of Longitude. The Areas at Mean Low Water and at Successive Depth Intervals Were Measured Planimetrically. The Depth Intervals, Listed in Feet, Were Largely Taken from Contours Printed on the Charts, but a Few Additional Contours Were Drawn with the Aid of the Soundings. The Areas Listed Here Include Fishers Island Sound but Not the Waters South and East of Fishers Island, Gull Islands, etc.

	Area M. L. W. Naut. sq. mi.	*Volume in m³ x 10⁷ between successive depth contours*										*Total vol.*
		0–20	*20–30*	*30–45*	*45–60*	*60–75*	*75–100*	*100–125*	*125–150*	*150–175*	*175+*	
71° 50′–72° 00′	15.8	25	6	3	—	—	—	—	—	—	—	34
72° 00′–72° 10′	38.0	76	34	41	33	28	38	35	30	24	47	386
72° 10′–72° 20′	59.0	115	52	72	67	63	89	62	32	9	—	561
72° 20′–72° 30′	80.5	158	71	96	82	66	72	39	21	5	—	610
72° 30′–72° 40′	116.7	234	109	148	132	102	72	6	1	—	—	804
72° 40′–72° 50′	128.8	257	119	159	142	128	118	18	1	—	—	942
72° 50′–73° 00′	130.0	256	114	151	124	98	101	37	8	—	—	889
73° 00′–73° 10′	99.6	195	85	108	88	67	74	37	11	—	—	665
73° 10′–73° 20′	98.0	194	87	116	92	57	49	16	—	—	—	611
73° 20′–73° 30′	70.7	127	49	59	45	32	28	9	2	—	—	351
73° 30′–73° 40′	54.2	97	38	46	26	10	6	1	—	—	—	224
73° 40′–73° 50′	37.4	59	18	18	12	—	—	—	—	—	—	107
Total	928.7	1793	782	1017	843	651	647	260	106	38	47	6184

interpretation of biological and chemical observations that were made at the same time and which will be described in subsequent papers.

It is not the purpose of the writer to present a detailed account of the mass of accumulated information, which is likely to be of interest only to local investigators. Instead, small samples of data and condensed summaries have been prepared in an attempt to evaluate principles of temperature and salinity distribution that will be of more general interest.

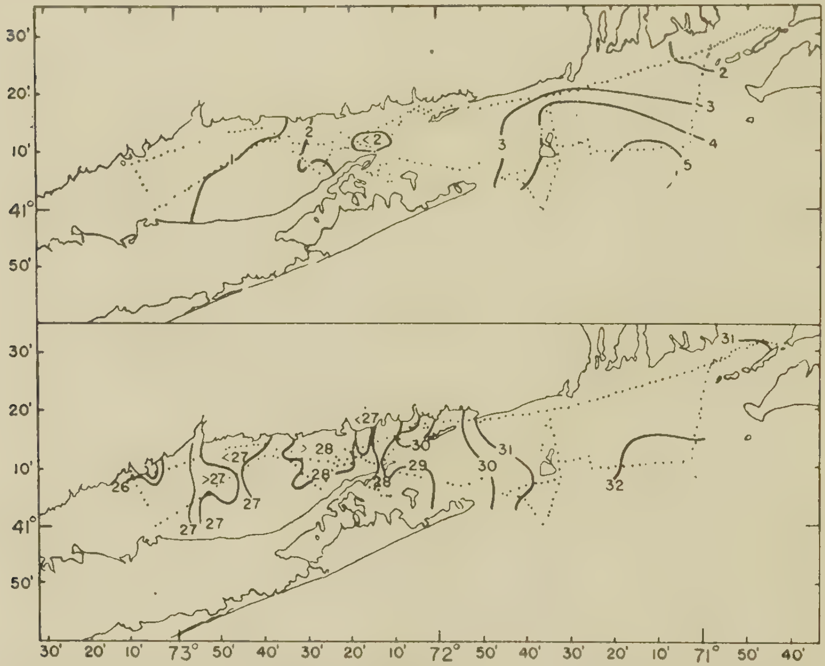

Figure 2. Distribution of surface temperature in °C (top) and salinity in °/₀₀ (bottom) during Cruise 1, January 22 to February 8, 1946.

SALINITY AND TEMPERATURE DISTRIBUTION

Various earlier studies have demonstrated the existence of a slow southwesterly drift of water along the continental shelf off southern New England. Part of this water is diverted into the sounds, where it is gradually freshened by admixture with coastal drainage. The product of admixture is gradually removed from the sounds, and Figs. 2 to 5 indicate that the major outflow occurs between Montauk Point and Block Island. Generally this drainage is revealed only by a bending of the isohalines around Montauk Point and a general increase in salinity toward the east and north, but occasionally, as in Fig. 3, there appears to be a discrete mass of low-salinity water traversing the area.

In the semi-enclosed basins of L. I. S. and Gardiners Bay, and to a lesser extent in Vineyard Sound and Buzzards Bay, the salinity decreases from the entrances toward the inner portions as a result of progressive dilution by river drainage. The charts show examples of various stages in the mixing process between river water and the main body of coastal water, including pockets of very fresh water at the immediate mouths of the rivers as well as larger and more diffuse eddies that have been carried away by the tide. Occasionally, more detailed observations have been obtained by towing an automatically recording conductivity cell. A highly irregular distribution of salinity was found within the freshwater patches, often consisting of

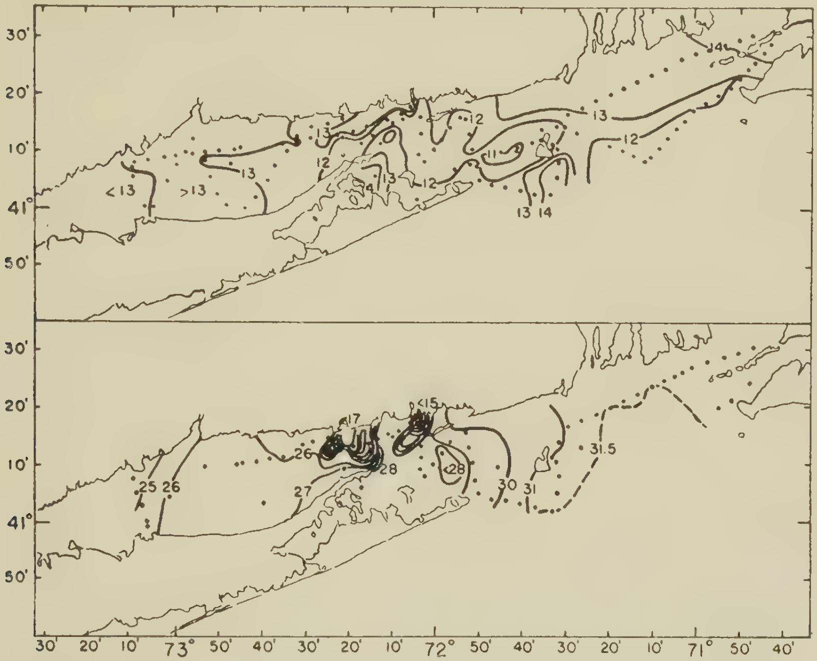
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Figure 3. Surface temperature and salinity during Cruise 4, May 31 to June 7, 1946.

alternating streaks of high and low salinity which were demarked by rips on the surface as well as by a change in turbidity. Such structures moved and changed continually with the tide and appeared to be largely dissipated within a few hours. Thus the charts are compounded of large-scale features that changed little between the outbound and homeward passages of the vessel and small-scale structures that probably changed significantly while they were being traversed.

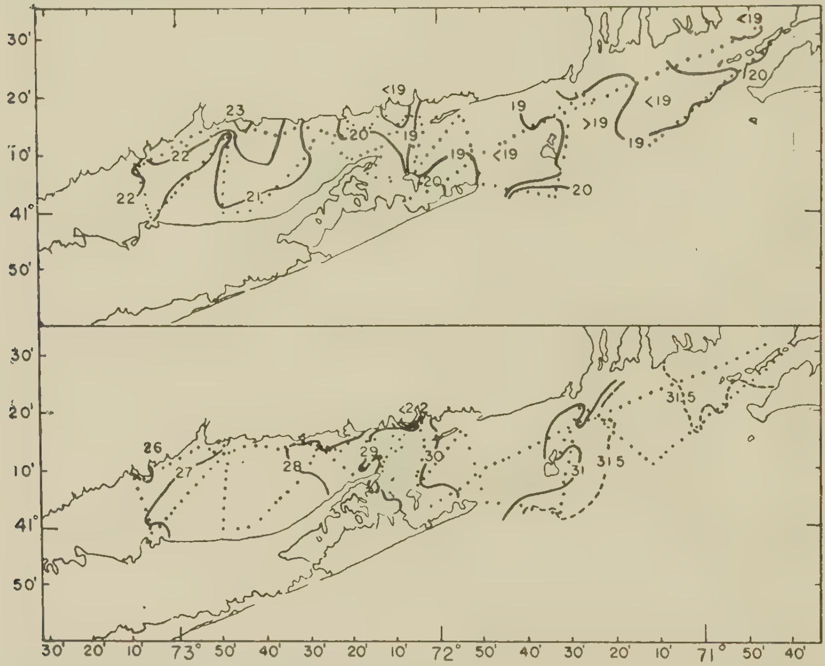

Figure 4. Surface temperature and salinity during Cruise 6, August 20 to 25, 1946.

Galtsoff and Loosanoff (1939) recorded the surface and bottom temperatures and salinities at numerous stations in L. I. S. during three cruises in May–June, August–September, and December, 1935. They reported a seasonal variation in salinity that is confirmed in the present survey. The largest seasonal range is found in the western part of L. I. S., where it reaches a magnitude of two or three parts per mille, the minimum salinity occurring in spring, the maximum in autumn, corresponding to the seasonal variation in river drainage. In the relatively open waters between Block Island and Marthas

Vineyard, the charts show a smaller but otherwise similar variation of $1^{\circ}/_{\circ\circ}$.

Subsurface salinity measurements revealed small vertical salinity gradients throughout most of the area. The increase between surface and bottom was seldom more than $1^{\circ}/_{\circ\circ}$ except in the vicinity of river mouths.

The midwinter surface temperature was 4–5° C off Block Island and decreased toward the freezing point in inshore waters. Conversely, summer temperatures near the coast were generally a few degrees higher than those in the outer part of the area. The total seasonal range was of the order of 15° off Block Island and 20° in much of the coastal zone. According to data published by Prytherch (1929) and Riley (1941), the shallow waters of harbors and inlets have an annual range of about 25°.

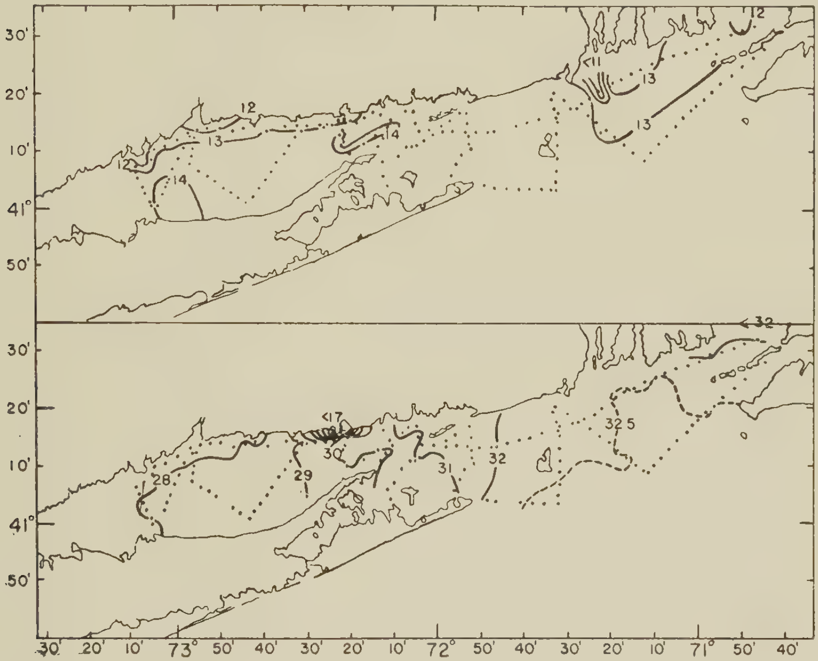

Figure 5. Surface temperature and salinity during Cruise 8, November 13 to 17.

Strong thermal stability was found only in the outer waters off Block Island, where in midsummer there was a sharp thermocline with a temperature decrease of about 10°, centered at a depth of 15–20 m. In the remainder of the region there was usually a temperature decrease of 1–2° between surface and bottom during the spring and summer. Occasionally the gradient was as much as 5°. In winter, positive gradients were common, and increases of as much as 1° between surface and bottom were recorded.

The charts show that localized patches of low-salinity water sometimes had distinctive temperature characteristics. In winter they tended to be colder than the surrounding water of higher salinity, and in summer warmer. To some extent this may have been due to the fact that the seasonal temperature cycle of the rivers is marked. However, it is regarded as more important that the eddies had strong vertical stability, as indicated by salinity gradients, so that the effects of surface heat exchange were intensified.

TIDES AND TIDAL CURRENTS

The tide moves into B. I. S. as a progressive wave. Low water at Block Island precedes low water in the eastern end of L. I. S. by an hour and a half. This in turn precedes low water in the western end of L. I. S. by two hours. Here the tide becomes essentially a standing wave. Throughout the central and western parts of L. I. S., the time of slack water nearly coincides with high and low tides, but toward the eastern end, the ebb current follows high tide by an hour and a half or more. The mean range of the tide is about 0.75 m along the shore of B. I. S. and the eastern part of L. I. S. and increases in a westerly direction to 2.2 m. The corresponding spring ranges are 0.95 and 2.6 m. Theoretical aspects of the tides in this region have been treated by Redfield (1950), and further discussion is unnecessary.

Surface tidal currents have been measured by the U. S. Coast and Geodetic Survey and published in the form of hourly charts covering a complete tidal cycle. These are summarized in Fig. 6 as average flood and ebb velocities. The original Survey charts show that the current turns at nearly the same time throughout both Sounds. Thus the lag in the time of the tide, described above, is a fairly precise indicator of the degree of transition of the tidal wave from the progressive to the standing type.

Data on the height and time of the tide from the U. S. Coast and Geodetic Survey tide tables provide a means of estimating the magnitude of tidal transport in L. I. S. A 24-hour period was chosen when the predicted tides approximated the mean range. The tidal height was computed for hourly intervals during this period throughout L. I. S. By summing hourly changes in volume for successive small areas, the total inflow and outflow during a tidal cycle was found to be 8.2% of the volume below mean low water.

Tidal exchanges in B. I. S. cannot be determined with any degree of precision. The change in the volume of water is only 2–3%. But since it also supplies and receives the tidal volume of L. I. S. and Gardiners Bay, the total exchange of water may be nearly an order of magnitude greater.

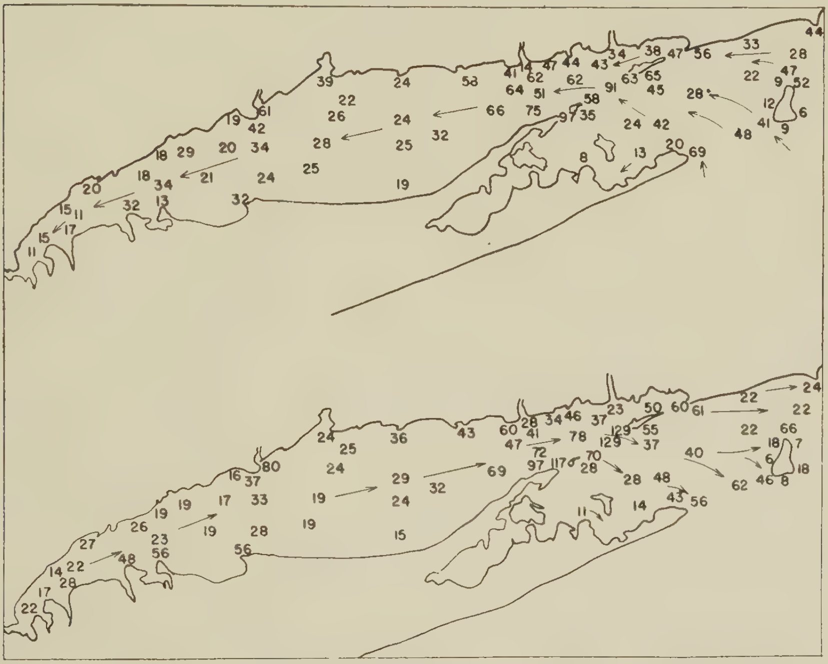
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Figure 6. Average velocity in cm per second of the flood (top) and of the ebb (bottom) surface currents.

The volume computations described above were used to estimate the average east-west tidal velocity through half a dozen cross-sectional areas of L. I. S. The calculated velocities in any given area were in most cases within the limits of variation of the measured surface values given in Fig. 6. Average surface values were somewhat higher, as might be expected. The difference ranged from about 10%

in the eastern and central parts of the Sound to nearly 50% in the constricted western portion.

NONTIDAL SURFACE MOVEMENTS

Fig. 6 reveals differences between flood and ebb velocities which are in some cases very marked. Such differences may be ascribed to the following causes:

1. Errors of measurement.
2. Small-scale oceanographic variations. These may be of a random nature, such as eddies and wind drifts, or they may be consistent differences of a very local nature due to peculiarities of bottom topography.
3. Rotation of the tides. While the predominant tidal movement is an east-west oscillation, the Coriolis force must tend to produce a clockwise rotary movement. Prytherch (1929) measured tidal currents with an Ekman meter in a limited area along the Connecticut shore and found a clockwise rotation during the latter half of the flood. However, in neither the current measurements in Fig. 6 nor in Redfield's (1950) theoretical treatment of the subject is there an indication of a broad-scale rotary movement.
4. Large-scale nontidal movements generated by the pressure distribution.

The present section will deal with the question of whether there exists in this region a consistent or prevailing residual drift, and if so, what the pattern of circulation and the generative forces might be. Drift bottle records, current measurements, and the distribution of conservative concentrations will be brought to bear on these problems.

Drift Bottles. Prytherch (1929) described a series of experiments in which 500 drift bottles were released during the period of September 18–21, 1926 near the Connecticut shore east of the mouth of the Housatonic River. The majority of recoveries during the first week or two were on the Connecticut shore, east and west of the point of release. At progressively later intervals there were returns from the opposite shore, from the eastern part of L. I. S., and from the shores of B. I. S. There were 203 recoveries during the first month and a total of 290 in ten months. Prytherch presented charts of the positions of release and recovery in six of the experiments. Fig. 7 summarizes these experiments as numbers of recoveries within designated strips of the shore line.

The drift bottle data were supplemented with current meter observations in the general area of bottle releases. There was an indication of a residual drift to the east. The evidence as a whole led Prytherch to the conclusion that the predominant drift in L. I. S. is a large-scale clockwise eddy, with a discharge of surface water out through the eastern passes.

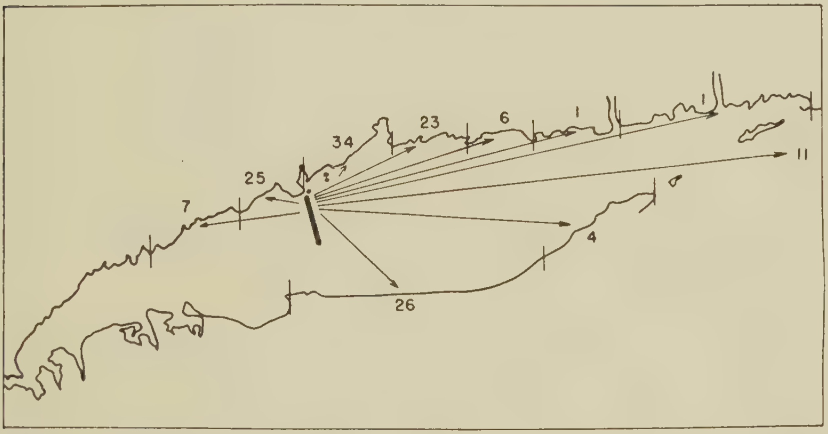

Figure 7. Summary of Prytherch's (1929) drift bottle experiments. Black spots show points of release. Figures indicate the number of recoveries along strips of shoreline delimited by vertical lines.

Current Measurements. The hourly current measurements of the U. S. Coast and Geodetic Survey were summed, and the resultant drift during the 12-hour tidal cycle was converted to an estimate of average residual velocity. The results are shown in Fig. 8A. It is only with considerable reservation that they can be accepted as evidence of a general circulation pattern. Random variability and errors of measurement are such that a nontidal movement cannot be detected unless it constitutes a sizable fraction of the tidal velocity. It is apparent in Fig. 8A that a considerable number of the velocities are large enough to reduce technical errors to insignificance. It is not so easy to evaluate small-scale oceanographic variability. The only criterion available is consistency of the results. As a specific example, in the north central part of L. I. S. there is an estimated velocity of 6 cm/sec eastward along the Connecticut shore. The observation was obtained in a channel between the mainland and an offshore island and reef. It disagrees as to current direction with other coastal observations to the east and west. It might be regarded as a local aberration. However, two stations in more open waters to the south and west also indicate an easterly drift. It so happens that both of these have small and relatively insignificant velocities. But, although all of the observations are open to suspicion individually, the existence of three consistent results increases the statistical probability of a general eastward drift in this part of L. I. S.

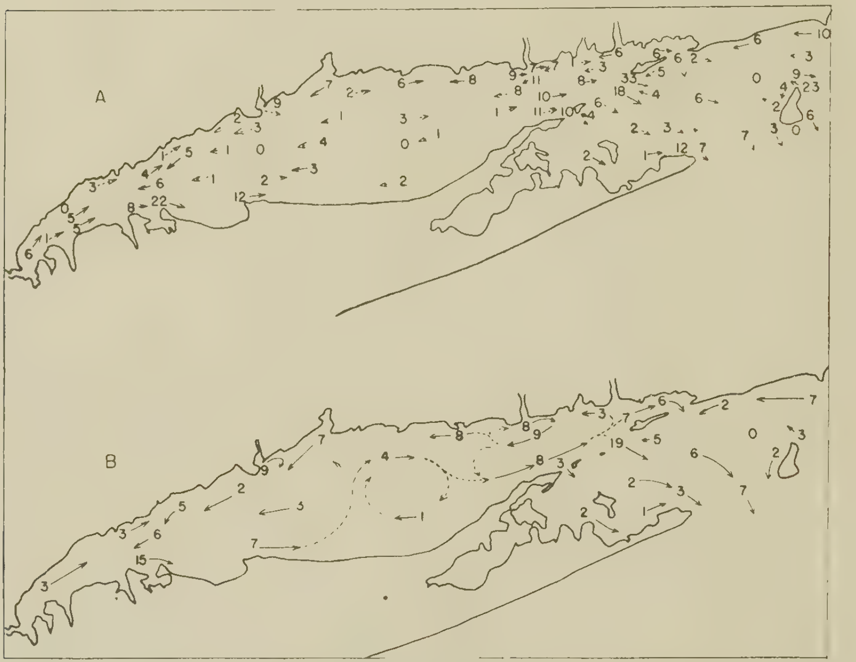

Figure 8. Residual surface drift in cm per second. *A*. Difference between flood and ebb velocities (Fig. 6) averaged for a complete tidal cycle. Solid arrows indicate that the residual drift is more than 15% of the tidal displacement; broken arrows, less than 15%. *B*. Schematic diagram of currents obtained by combining and averaging data in *A*.

Fig. 8B shows a simplified and schematic current diagram obtained by combining and averaging adjacent observations in Fig. 8A. It is apparent that this treatment entails subjective judgments as to which observations are best combined. Its only purpose is to facilitate examination and discussion; possible distortions should be borne in mind.

The results thus far obtained suggest a complicated circulation pattern in L. I. S. which is briefly summarized as follows: There appears to be a surface drift into L. I. S. at the western end which merges with a counterclockwise current following the shore line in the western third of the area. This gives way to weak and confused currents in the broad central portion. Here the requirements of continuity and the measured drifts, such as they are, suggest that there may be a weak clockwise eddy. Another clockwise eddy, of small size but with strong currents, is found between the mouth of the Connecticut River and Long Sand Shoal. Both of these eddies probably supply water to an eastward drift that follows the Long Island shore and moves out through the eastern passes. In B. I. S. there appears to be a predominant westward drift between Point Judith and Block Island which eventually merges with the L. I. S. effluent and passes out to sea between Block Island and Montauk Point.

The Relation between Currents and Density Distribution. Possible agencies in the generation of currents in L. I. S. are (a) the Coriolis effect on tidal flow, and (b) horizontal density gradients. Rotary tides might produce a simple clockwise residual drift of the type postulated by Prytherch. But the more extensive observations by the U. S. Coast and Geodetic Survey indicate that this type of circulation, if it exists at all, is limited to the central part of L. I. S. Elsewhere, if the circulation pattern outlined in the previous section is correct, it must be primarily a system of density currents. It is desirable, therefore, to examine the distribution of density in L. I. S. to see whether or not it provides a reasonable explanation for the observed currents that were shown in Fig. 8.

Fig. 9A shows the surface density distribution during the cruise of August 20–25, 1946, calculated from temperature and salinity data previously illustrated in Fig. 4. It differs only in minor details from the pattern that would be derived by considering only the effect of salinity on density. During the remainder of the year, temperature gradients were even less important, and the salinity distribution in Figs. 2 to 5 will provide an adequate basis for the discussion of density gradients.

So far as can be determined from the available data, horizontal variations in density are not simply surface phenomena; a similar degree of variability occurs in the bottom waters. This is illustrated in Fig. 9B, which is redrawn from a chart by Galtsoff and Loosanoff (1939) whose data on bottom waters were more complete than those obtained in the present survey.

In deep oceanic waters, density gradients of the magnitude observed in L. I. S. would allow no doubt as to the existence of currents. For example, assume a layer of water 10 m thick with a lateral change in density of one sigma-*t* unit in four miles. Assuming a surface of no motion at the bottom of the layer, dynamic computations show that the mean velocity at the sea surface (in the latitude of L. I. S.) would be of the order of 12 cm/sec. Along the northern shore of L. I. S. it is common to find density gradients equal to or greater than the one postulated. Farther off shore, where the density gradients are smaller, similar calculations lead to estimates of 5 cm/sec or less.

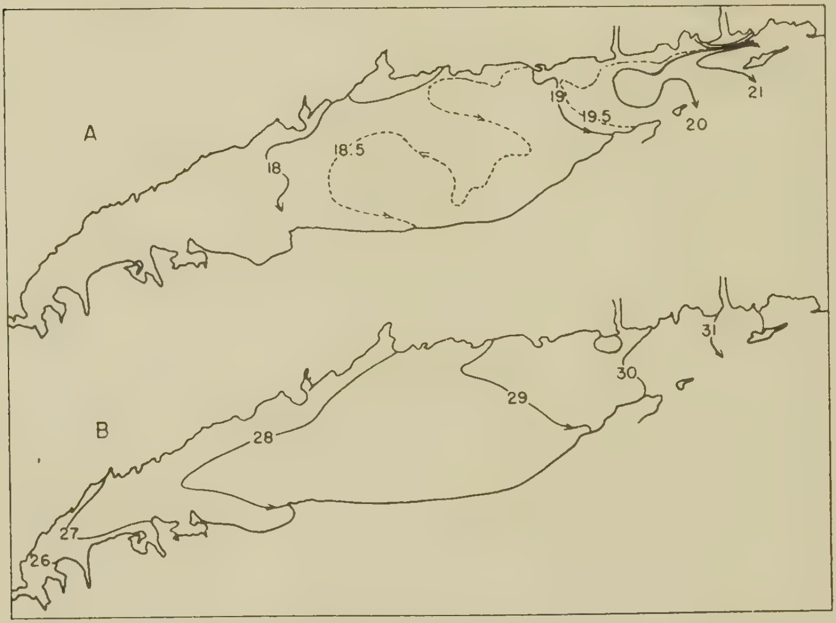

Figure 9. *A*. Surface density distribution, August 20–25, 1946. *B*. Bottom salinity distribution during August–September 1935 (after Galtsoff and Loosanoff, 1939). Arrows indicate the direction of propagation of currents related to the distribution of density.

The hypothetical cases are suggestive of the magnitude of the forces tending to produce density currents in L. I. S. However, it is not possible to make due allowance for frictional terms nor to designate a correct depth for the surface of no motion, if any. Hence, simple dynamic theory cannot be applied to these waters with any degree of accuracy, and even the qualitative interpretation is somewhat uncertain. In deep water one would expect that the lines of equal density would approximate the dynamic topography of the sea surface and that the movement of water would follow the arrows as indicated in Fig. 9. While the major part of this pattern agrees with the current measurements in Fig. 8, the scheme as a whole is impossible from the standpoint of continuity. It seems possible that water movements generated in the northern part of L. I. S. where the density gradients are strongest, evolve into a persistent but non-steady state distribution of currents in which continuity is established by movement across isobaric surfaces in the southern part of L. I. S. where the density structure is weakest.

In brief, freshwater drainage tends to set up a simple counterclockwise movement of water in L. I. S. However, the necessary pattern of density distribution is never quite realized; it is continually weakened by lateral diffusion associated with the strong tidal oscillation, particularly along the Long Island shore where the freshwater supply is least. The net result is a series of eddies instead of one.

Summary of Surface Currents. A variety of evidence has been brought to bear on the problem of surface currents—drift bottles, current measurements, and density distribution. These cannot be synthesized into an entirely consistent picture; nevertheless, the composite diagram shown in Fig. 10 indicates general agreement as to the major features of the circulation pattern. The long solid arrows in Fig. 10 indicate the direction of propagation of density currents as determined by a more or less typical salinity distribution (Fig. 4, supplemented by data on the western part of L. I. S. from 9B). In the southern part, these arrows are terminated well offshore, since the isohalines cannot indicate properly the direction of flow, and the density distribution probably impedes movement rather than propagating it.

The short solid arrows are the residual drifts from Fig. 8A. Short dotted arrows postulate an onshore set in two areas where most of Prytherch's drift bottles were grounded. Of the bottles recovered in L. I. S., 85% were returned from these two strips, which constitute less than 50% of the shore line. None was recovered west of Darien, Connecticut nor on the Long Island shore west of Port Jefferson.

Such a complete separation cannot be accounted for simply by the distance from the point of release. Hence an offshore set is indicated by short dotted arrows in the western area.

In the central part of L. I. S. the observations are less complete than elsewhere. Long dotted arrows indicate a possible pattern of currents which is based on the weak density gradients shown in Fig. 9A. Obviously a drift to the north is necessary in order to satisfy continuity. Moreover, the postulated pattern requires a convergence of currents on both the Long Island and Connecticut shores (and subsequent deflection offshore) at points which mark approximately the centers of the major drift bottle recoveries.

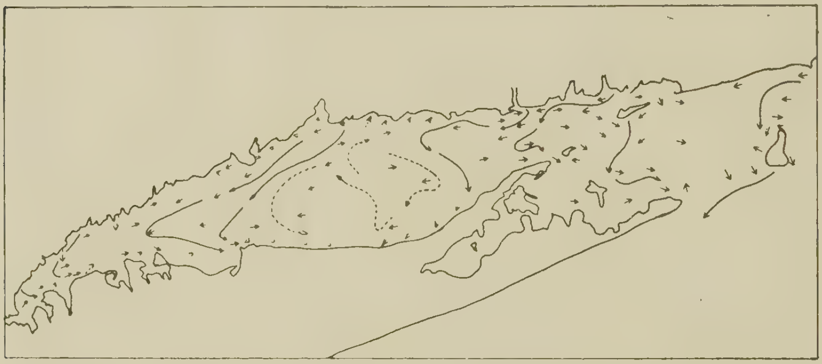

Figure 10. Composite diagram of surface currents. For explanation, see text.

Some of the features that have been discussed may be quite variable. During periods of heavy river drainage, the fresh water is sometimes carried well out into the Sound. Probably it forms clockwise eddies that alter the circulation pattern locally. The effect is likely to be greatest off the mouth of the Connecticut River. Ordinarily there appears to be a pool of fresh water and a clockwise eddy between the mouth of the river and Long Sand Shoal. But when the fresh water extends far beyond the Shoal, as in Fig. 3, the compact system of currents in the eastern end of L. I. S. must be changed considerably. Fig. 3 also suggests that such eddies may break away intact and move out into B. I. S.

Currents in the central part of L. I. S. are probably particularly variable. The salinity distribution changed from one cruise to the next, but the possible changes in currents are too uncertain to warrant discussion. The early recoveries in the drift bottle experiments, first to the east and then to the west of the point of release, are not entirely explained by the pattern of currents in Fig. 10. The results would seem more reasonable if the central eddy were displaced some ten miles westward at the time of the experiments.

THE CONSERVATION OF MASS AND SALT WITHIN LONG ISLAND SOUND

Freshwater Drainage. Further inquiry into the physical oceanography of L. I. S. will include estimates of mass transport, the exchange of water and salt between L. I. S. and B. I. S., and effects of turbulence. A prerequisite to all such work is a quantitative knowledge of the rate of addition of fresh water to L. I. S. Data largely from Suttie (1928) show that three rivers supply the major inflow. The Connecticut River ranks first with a drainage basin of 11,200 sq. mi. (statute); the Housatonic River drains 1,930 sq. mi. and the Thames River 1,400. Smaller rivers and streams of Connecticut, Long Island, and the mainland of New York State contribute drainage from 1,290 sq. mi. Thus the total drainage basin of L. I. S. is 15,900 sq. mi.

Data on river discharge during 1946 were obtained from the water supply papers of the U. S. geological Survey, as follows: (a) Observations on the monthly discharge of the Connecticut River from a gauging station at Thompsonville, Connecticut, which measures the drainage from 9,661 sq. mi. of the basin. (b) Similar observations for the Housatonic River at Stevenson, Connecticut, drainage basin 1,545 sq. mi. (c) Data on average monthly discharge per square mile of drainage basin for three smaller rivers, the Shetucket, Quinnipiac, and Saugatuck (respectively 401, 109, and 77.5 sq. mi.). Items (a) and (b) were used directly; they constitute 70% of the total drainage basin of L. I. S. It was assumed that the remaining 30% could be estimated with sufficient accuracy by applying the average of (c). The results are shown in Fig. 11. The average fresh water drainage during 1946 was 679 m^3/sec. The total was 214 x $10^8 m^3$, or about 35% of the volume of L. I. S. below mean low water.

The total freshwater increment includes rainfall on the surface of the Sound as well as river drainage. According to the Monthly Weather Review, the mean rainfall in New England in 1946 was 38.41 inches (98 cm).

In problems involving the conservation of mass and salt, an allowance must be made for the loss of water by evaporation. It has not

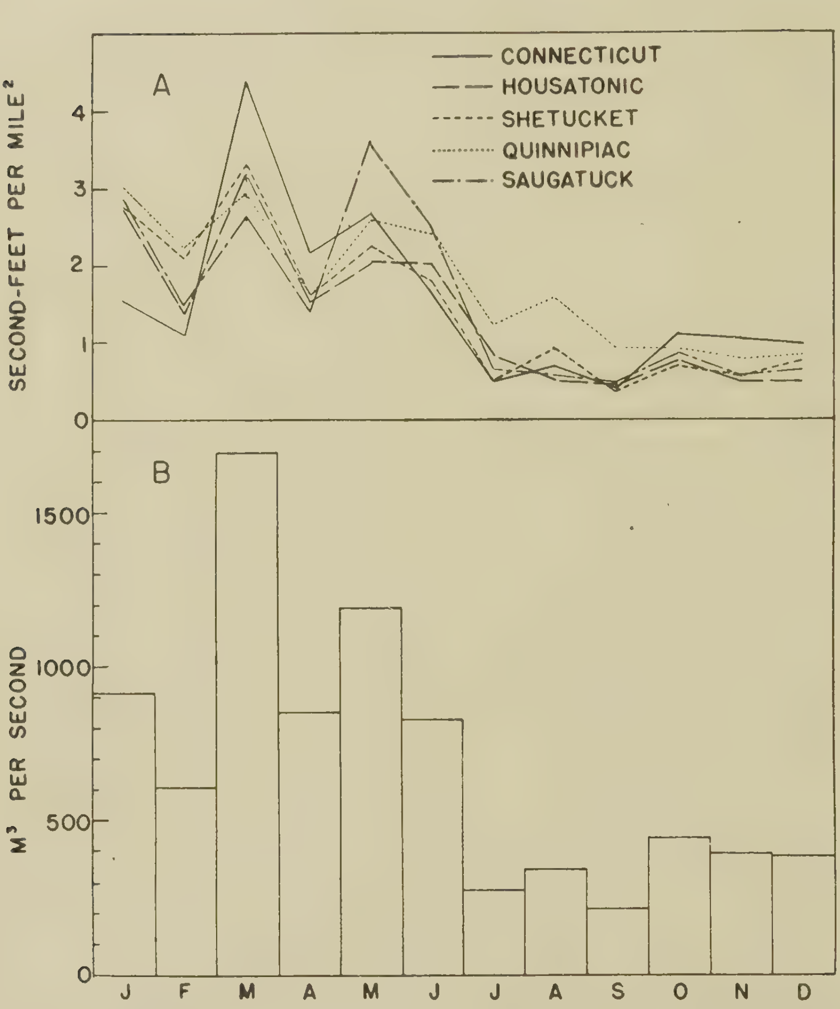

Figure 11. Freshwater drainage. *A*. Runoff in cubic feet per second from each square mile of the drainage basin of five Connecticut rivers. *B*. Estimated mean monthly drainage into L. I. S. during 1946.

been computed or measured, but general information on oceanic evaporation (Sverdrup, et al., 1942: 123) indicates that the total evaporation loss is about the same as the 1946 rainfall. Therefore the net increment of fresh water will be assumed to equal the river drainage in Fig. 11.

Mass Transport. Freshwater drainage creates a small hydraulic head of water such that over a period of time there must be a corresponding net transport of water from L. I. S. Superimposed upon the net transport is a series of exchange transports between L. I. S. and the adjacent waters. The largest of these of course is the tidal exchange. Only the net and tidal transports can be described with a satisfactory degree of accuracy. However, certain other aspects of the transport system are so important that an attempt must be made to evaluate them.

Fig. 8 shows that surface water moves through L. I. S. from west to east. At the westernmost point of current observation in the Sound, the residual surface velocity was 6 cm/sec. The cross section of the channel at this point is about 37,000 m^2. Thus, if the current extended from surface to bottom and averaged about two-thirds of the surface velocity (cf. Sverdrup, et al., 1942: 568), the mass transport into L. I. S. at this point would be about 1,500 m^3/sec. However, farther to the west, in the constricted part of the channel known as the East River, current observations have indicated a residual drift in the opposite direction, toward New York Harbor and the open sea. The source of these divergent surface movements must be upwelling water from deeper layers. Thus there is no certainty of a mass transport into L. I. S. at the western end. Probably there will be no great error if the transport is assumed to be negligible.

In the eastern passes both the observed surface velocities and the cross-sectional areas are much larger than those in the western channel. A calculation that assumes, as before, a mean eastward velocity in the passes equal to two-thirds of the surface velocity yields a transport of 34,000 m^3/sec. This is 45 times the net transport, a difference that could hardly be due to ordinary observational error. Possible alternatives are that the movement occurs only in a very thin surface stratum 1–2 m thick, or that there is a two-layered transport system such that water flows out at the surface and into L. I. S. at a deeper level.

Fig. 8 shows that surface currents followed lines of equal density where it was possible to do so without violating continuity. In the eastern end of L. I. S., the density structure agrees with observed currents; the outflow is probably essentially a density current. It would not be realistic to suppose that the usual mathematical relations between dynamic topography and current velocity are quantitatively applicable to an area where the water is squeezed through a series of channels and is subjected to intense bottom friction. However, it may be useful to prepare a maximum estimate of transport by the application of dynamic theory to the observed density distribution. For this purpose, two stations were chosen from each cruise (except Cruise 5, in which the data were inadequate), one in B. I. S. a few miles to the east of the passes (at about 41° 12′ N, 71° 50′ W), the other in the eastern part of L. I. S. (at about 41° 15′ N, 72° 10′ W). The first column in Table II shows the southward transport between these stations relative to the 30-meter depth, which is near bottom in B. I. S. and approximates the mean depth of L. I. S. at this longitude.

TABLE II. TRANSPORT COMPUTATIONS—EXCHANGE BETWEEN THE LONG ISLAND AND BLOCK ISLAND SOUNDS IN M³/SEC.

Cruise	*Maximum transport*	*Drainage*		*Surface outflow*	*Bottom inflow*
		Period	*m³/sec*		
1	70,800	Jan.	910	18,860	17,950
2	73,500	Feb-Mar.	1,150	20,820	19,670
3	86,000	Mar.-Apr.	1,270	23,730	22,460
4	28,100	Apr.-May	1,020	8,660	7,840
6	54,500	July-Aug.	310	11,610	11,300
7	28,600	Sept.-Oct.	330	6,970	6,640
8	35,500	Oct.-Nov.	420	7,960	7,540
9	40,200	Nov.-Dec.	390	9,930	9,540

The average of the transport computations is larger than the rough estimate of 34,000 m³/sec based on observed currents in the passes. It is much larger than the generalized estimate of drainage during the preceding month or two, which is shown in the next part of Table II. However, there are reasons for believing that the transport estimates are much too large, aside from the matter of frictional effects. In the first place, the effect of freshwater drainage is not merely to create a hydraulic head by the addition of mass to L. I. S. It also tends to create a slope in the free surface by reducing the density of the water mass as a whole. It follows that the surface outflow will exceed the net transport, and to maintain continuity of mass there must be a compensating inflow of deeper water.

Second, it is arbitrary to fix 30 m as a depth of no motion. It is more realistic to assume that the net transport is correct. In that case the average depth of the surface of no motion must be reduced; there will be a southerly transport above this depth and a northerly one below. The dynamic computations are readily altered to fit this concept by subtracting a systematic correction from the transport values for successive depth intervals. The results are shown in the last two columns of Table II.

The figures so obtained are still maximal estimates, since no allowance has been made for frictional retardation. However, the discrepancy between net and total transport has been removed, and the computed surface currents are of the order of magnitude of the observed values. Total transports in the upper 5 m, divided by the cross-sectional area of the upper 5 m of the passes, yield estimates of 5–16 cm/sec, as compared with observed velocities of 6–33 cm/sec. Moreover, the concept that dilution by river drainage is fundamentally responsible for the maintenance of a two-layered transport system is supported by the fact that there is a correlation between the amount of drainage and the mass transport data in the last column of Table II.

TABLE III. Mean Salinity at a Station in B. I. S. at About 41° 12′ N, 71° 50′ W and in L. I. S. within the Listed Longitude Ranges

	Cruise							
L. I. S.	*1*	*2*	*3*	*4*	*6*	*7*	*8*	*9*
72–10 to 72–20 W	28.46	28.12	28.97	28.35	29.76	29.60	30.80	30.28
72–20 to 72–30 W	28.73	26.99	27.14	27.44	28.31	29.56	30.40	29.80
72–30 to 72–40 W	27.83	26.80	27.74	26.52	27.61	28.46	28.80	28.94
72–40 to 72–50 W	27.11	26.66	27.01	26.72	27.52	27.86	28.50	28.47
72–50 to 73–00 W	27.11	26.40	27.08	26.75	27.04	27.72	28.20	28.38
73–00 to 73–10 W	26.78	26.31	26.52	26.06	27.13	27.50	28.20	28.20
72–10 to 73–10 W	27.59	26.81	27.35	26.91	27.71	28.34	29.00	28.91
B. I. S.	31.03	30.17	30.54	29.61	30.59	31.23	31.90	32.02

If the postulated mechanism is correct—that freshwater drainage regulates the amount of inflow of more saline water from B. I. S.—it regulates the salinity at a more nearly uniform level than would otherwise be possible.

The Total Exchange of Water and Salt between the Two Sounds. If the net transport described above were the only movement of water in the eastern passes, L. I. S. would be diluted about 35% each year. Maintenance of an approximately constant salinity through the years requires the transfer of salt from B. I. S., by mass transport or by diffusion, in sufficient quantity to offset the tendency toward dilution. An elementary application of the principle of salt continuity is sufficient to determine the total amount of B. I. S. water that must be brought into L. I. S. during a given period in order to maintain the observed salinity.

Table III lists salinity data that will be used for the exchange computation and for other calculations later. Values for B. I. S. were obtained by averaging the salinity, surface to bottom, at a station a few miles east of the mouth of L. I. S. Within L. I. S. the observations were averaged on a volumetric basis; i. e., the product of the mean salinity of successive layers and the volume of water in each layer was summed from surface to bottom and divided by the total volume of water. By this method it is possible to deal with the salinity of the water mass as a whole and to ignore, for the moment, the effects of vertical diffusion.

TABLE IV. COMPUTATION OF EXCHANGE BY THE METHOD OF PROPORTIONAL PARTS

	Cruises						
	1–2	*2–3*	*3–4*	*4–6*	*6–7*	*7–8*	*8–9*
Mean salinity B. I. S.	30.60	30.35	30.08	30.10	30.91	31.57	31.96
Fresh water, $10^6 m^3$	4,547	3,666	3,352	3,352	1,171	1,315	1,546
m^3/sec.	1,080	1,020	1,200	470	280	440	390
% of L. I. S.	7.34	5.93	5.42	5.42	1.90	2.13	2.50
B. I. S. inflow, m^3/sec.	4,610	12,400	7,060	8,380	6,700	10,240	3,050
L. I. S. outflow, m^3/sec.	5,690	13,420	8,260	8,850	6,980	10,680	3,440

Further steps in the exchange computation are shown in Table IV. The first line is the mean salinity between successive cruises at the B. I. S. station, obtained by averaging the data in Table III. The next line is the total freshwater drainage between cruises, which is listed also as mean flow in cubic meters per second and as a percentage of the total volume of L. I. S. If mixing processes in L. I. S. are rapid enough so that the fresh water is distributed fairly uniformly, the following type of calculation is permissible:

In the east-central part of L. I. S., where the mean salinity was 27.59°/₀₀ during the first cruise, addition of 7.34 parts of fresh water per 100 parts of L. I. S. water between Cruises 1 and 2 would reduce the salinity to $27.59 \times 100/107.34 = 25.74$°/₀₀. However, the observed salinity at the time of the second cruise was 26.81°/₀₀. If the difference were due to the introduction of x parts of B. I. S. water with a mean salinity of 30.60°/₀₀, then

$$100\ (27.59) + 7.34\ (0) + 30.60x = (107.34 + x)\ 26.81,\ x = 31.3\%.$$

Thus the estimated introduction of B. I. S. water between Cruises 1 and 2 was 31.3% of the volume of L. I. S. From the volume of L. I. S. and the time interval between cruises,

$$\text{Inflow from B. I. S.} = \frac{.313 \times 6{,}184 \times 10^7 \text{m}^3}{4.2 \times 10^6 \text{ sec}} = 4610 \text{ m}^3/\text{sec.}$$

To maintain a constant mass of water in L. I. S., the mean outflow must equal the sum of drainage and inflow, or 5,690 m^3/sec. This and similar calculations for other cruise intervals yield the estimates shown in the last two lines of Table IV.

The method that has been described is simpler and less precise than Ketchum's (1951) treatment of the flushing of estuaries. The latter is not easily applied to L. I. S., with its complicated drainage and circulation pattern. Nearly 80% of the drainage (Connecticut and Thames Rivers) is introduced into L. I. S. within a few miles of the eastern passes. Its influence on the western part of L. I. S. is uncertain and probably variable. The method that has been described is perhaps the most accurate way of obtaining an estimate of the total exchange between the two Sounds, but it is not easily elaborated into a study of the exchange through successive cross sections of L. I. S.

The data in Table IV have meaning only as a statistic; they tell nothing about the processes effecting the transfer of salt. If the latter resulted solely from mass movements, the transport would be less than the maximum estimate based on dynamic topography. The nontidal velocities in the passes would be of the order of 4–10 cm/sec. On the other hand, if the two-layered transport system postulated in the previous section were quantitatively insignificant, the transfer of salt might be accomplished by the random interchange of small water masses. The transfer would be described in terms of the salinity gradient and a coefficient of lateral eddy diffusivity. The latter is readily determined from the transport data as the product of the mean velocity of exchange per unit cross-sectional area of the passes (1.9–5.2 cm/sec) and the distance between the B. I. S. station and the eastern part of L. I. S. (about 2.7×10^6 cm). Thus the estimated range in the diffusion coefficient is 5×10^6 to 1.4×10^7 cm^2/sec.

The truth must lie somewhere between these extremes. Lateral diffusion is inevitable in an area of strong tidal exchange. The existence of a two-layered transport system is supported by the analysis of the density distribution and by the accompanying theoretical considerations. The dynamic computations provide a method of making a tentative estimate of the relative importance of advection and of diffusion. For example, (a) assume that the relative variation in transport in Table II is correct, but that the estimates are systematically too large (i. e., frictional retardation reduces the transport to a certain fraction of the values listed); (b) assume that there is no consistent relation between diffusion and transport. If these assumptions are correct, the actual transport can be estimated by a statistical comparison between the dynamic computations and the total transfer as determined in Table IV. A least squares treatment[3] indicates that the transport is 20% of the values obtained by dynamic computation and thus ranges from 1,400–4,200 m^3/sec. The remainder of the inflow, which is assumed to be part of the diffusion mechanism, has a mean value of 4,960 m^3/sec. The estimated average coefficient of eddy diffusivity is 6×10^6 cm^2/sec in the passes and 3.3×10^6 in the less constricted area in the eastern part of L. I. S., between 72° 00′ and 72° 10′ W.

LATERAL DIFFUSION IN LONG ISLAND SOUND

The mean salinity, surface to bottom, previously shown in Table III, will be used to estimate the magnitude of lateral diffusion in the central body of L. I. S. water between 72° 20′ and 73° 00′ W. The change in salinity from one cruise to the next will be examined by means of the simplified equation

$$\frac{\partial S}{\partial t} = \frac{A_x}{\rho} \cdot \frac{\partial^2 S}{\partial x^2} - V \frac{\partial S}{\partial x} + \frac{\partial S_f}{\partial t},$$

in which the time rate of change of salinity S is postulated to depend upon three factors: (a) horizontal diffusion, the product of the coefficient of eddy diffusivity A_x and the change in the salinity gradient per cm of horizontal distance x along the long axis of L. I. S., taken as positive eastward; (b) advection, the product of the net transport velocity V and the salinity gradient; and (c) the rate of change of salinity due to the addition of fresh water to the Sound $\partial S_f/\partial t$.

Table V shows the mean values for the terms in the equation, calculated for the periods between successive cruises. Details of the method of calculation are appended to Table V, showing the transformation of the original differential form to terms of finite differences. The values listed are used to solve for the one unknown term A_x, and the results are shown in the last line of Table V. The calculated coefficients are of the order of magnitude of the ones obtained by a slightly different method in the previous section. They also fall within the general limits of previously computed values for surface

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[3] The statistical method as applied here compares the average transport of two successive cruises (Table II) with the average inflow (Table IV) between cruises.

TABLE V. COEFFICIENTS OF HORIZONTAL EDDY DIFFUSIVITY IN L. I. S.*

	Cruises						
	1–2	*2–3*	*3–4*	*4–6*	*6–7*	*7–8*	*8–9*
Time, 10^6 seconds	4.2	3.6	2.8	7.1	4.2	3.0	4.2
$\Delta\bar{S}$	−0.78	0.54	−0.44	0.80	0.63	0.66	−0.09
$10^{11}\partial\bar{S}/\partial t$	−18.6	15.0	−15.7	11.3	15.0	22.0	−2.1
$10^3\Delta S_f$	−2.00	−1.61	−1.47	−1.48	−0.53	−0.61	−0.72
$10^{11}\partial S_f/\partial t$	−47.5	−44.6	−52.5	−20.8	−12.7	−20.3	−17.2
$10^{11}\partial S/\partial x$, 72-10 to 73-10	25.4	31.0	34.5	35.8	34.5	34.3	34.2
72-10 to 72-40	35.0	43.4	48.3	57.0	53.0	52.4	54.4
72-40 to 73-10	16.0	18.6	20.6	14.5	16.0	16.3	14.0
V, cm/sec.	0.20	0.19	0.22	0.09	0.05	0.08	0.07
$10^{11}V\partial S/\partial x$	4.9	5.9	7.6	3.2	1.7	2.7	2.4
$10^{17}\partial^2S/\partial x^2$	5.5	7.2	8.1	12.4	10.8	10.5	11.7
$10^{-6}A_x$	6.1	9.1	5.5	2.9	2.8	4.3	1.5

* From the time between successive cruises in line 1 and the change in the mean salinity in L. I. S. between 72-10 and 73-10 W (cf. Table III) in line 2, the time rate of change $\partial\bar{S}/\partial t$ is calculated in g/cm³/sec. ΔS_f is the product of the mean salinity and the percentage volume of freshwater drainage (Table II), which is then divided by the time to give the time rate of change of salinity due to dilution $\partial S_f/\partial t$. Next are listed three sets of east-west salinity gradients, based on the mean values in Table III. The first group is the difference between the salinity at 72-10 to 72-20 W and at 73-00 to 73-10 W, divided by the distance between the midpoints of these groups, 72-15 to 73-05, or 6.88 x 10^6 cm. Similarly, the gradients in the eastern and western halves of this area are determined separately by establishing an estimated mean salinity at the midpoint (72-40) as the mean of the data from 72-30 to 72-50. The velocity of net transport V is calculated from the total drainage in m³/sec and the mean cross-sectional area of the Sound. The next line shows the product of the velocity and the salinity gradients between 72-10 and 73-10. $\partial^2S/\partial x^2$ is the difference between the second and third gradients divided by the distance between the centers of the areas, 3.44 x 10^6 cm. Application of these data to the equation yields the coefficients of eddy diffusivity shown in the last line.

waters of the oceans, which Sverdrup, et al. (1942: 485) listed as about 10^6–10^8 g/cm/sec. That they lie near the lower limit of this range is to be expected in a relatively small body of water. The suggested seasonal variation, with the largest values in spring, may or may not be valid. The results are subject to considerable variation due to sampling error. Moreover, it is apparent that the net transport may be a serious over-simplification of the advection term. If the central part of L. I. S. has a two-layered transport system, such as was previously postulated for the eastern passes, the mixing effects of this transport will be included in the estimates of the diffusion coefficients. Therefore, the latter may be too high by an unknown and possibly variable amount. It is reasonable to suppose that lateral diffusion is primarily governed by the strength of the tidal currents. If this is so, the coefficients should be smaller in the central part of L. I. S. than in the eastern end, where the previous section suggested an average value of 3.3 × 10^6. Thus the lower values in Table V are probably more realistic than the higher part of the range.

VERTICAL EDDY CONDUCTIVITY

The seasonal temperature change provides a convenient means of estimating vertical turbulence, and the calculations can be carried out in greater detail than in the previous section because of the larger quantity of temperature records available.

For purposes of analysis, the part of L. I. S. between 72° 00′ and 73° 10′ W was divided into seven areas, each comprising 10 minutes of longitude and extending in a north-south direction across the width of the Sound. In each case the eddy conductivity was determined at depths of 10, 20, and 30 m, or at as many of these as the depth of water permitted.

In the absence of modifying effects due to advection and lateral conduction, the rate of passage of heat through a unit horizontal surface at a given depth z_1 is given by

$$A_z \frac{\partial \vartheta}{\partial z} = \int_{\text{bottom}}^{z_1} \frac{\partial \vartheta}{\partial t} dz ,$$

in which the product of the coefficient of vertical eddy conductivity A_z and the vertical temperature gradient $\partial\vartheta/\partial z$ at depth z_1 is equal to the time rate of change of temperature in the underlying water column. Tables VI and VII show the observed mean temperature gradients and the temperature change in the lower water between successive cruises. Application of these values to the equation yields the coefficients shown in Table VIII.

It is apparent that the equation is severely simplified. In the presence of horizontal temperature gradients in the lower water, horizontal diffusion and transport will modify the rate of change of heat and may cause a serious error in the estimate of vertical turbulence. A few calculations were made to assess these errors in terms of observed horizontal temperature gradients and of the previous estimates of net transport and lateral eddy diffusion. In no case did these effects account for as much as 1% of the observed temperature change. Nevertheless, Tables VI, VII, and VIII show that more serious errors exist. Question marks are inserted in Table VIII in places where the calculations yield negative values for the eddy coefficient. All such values were obtained in the eastern part of L. I. S., where it has been suggested previously that transport varies significantly with depth, thus invalidating the use of a mean transport

TABLE VI. Mean Temperature Decrease in °C x 10^{-2} per Cm of Depth in the Depth Range Listed. Each Value Is the Average for the Pair of Cruises. Cruise 5 Is Omitted because of Incomplete Data, and Cruise Intervals 1–2 and 6–7 Are Omitted because They Occurred Near the Minimum and Maximum Points of the Seasonal Temperature Cycle, When the Method Is Likely to Yield False Results.

Cruises	*Depth range (m)*	*72–00 to 72–10*	*72–10 to 72–20*	*72–20 to 72–30*	*72–30 to 72–40*	*72–40 to 72–50*	*72–50 to 73–00*	*73–00 to 73–10*
2–3	0–20	3.33	4.72	5.97	6.71	6.21	9.65	11.38
	10–30	−0.14	0.86	0.38	—	—	4.71	4.43
	20–45	−1.43	0.57	—	—	—	—	—
3–4	0–20	3.90	4.53	5.26	3.81	6.13	10.11	9.16
	10–30	−0.22	1.29	1.10	—	—	6.12	6.87
	20–45	0.70	0.95	—	—	—	—	—
4–6	0–20	2.73	3.08	3.95	4.93	6.05	9.34	6.98
	10–30	−0.35	1.06	0.98	—	7.01	7.97	7.85
	20–45	0.85	1.01	2.03	—	—	—	—
7–8	0–20	0.25	0.25	−1.52	−0.93	−1.72	−1.80	−0.46
	10–30	−0.78	0.05	−1.42	−0.79	−1.68	−2.25	−1.43
	20–45	−0.96	0.17	−1.08	—	—	—	—
8–9	0–20	−0.11	−0.57	−1.01	−1.85	−3.57	−3.03	−0.51
	10–30	−1.54	−0.73	−1.03	−1.32	−2.04	−3.13	−1.97
	20–45	−1.82	−0.69	−0.96	—	—	—	—

value for the whole vertical column. Here also, Table VII shows that the apparent rate of passage of heat through the 20 and 30-m levels sometimes exceeded that of the 10-m level. This presumably indicates advection. It probably means that warm surface water from B. I. S. sank and moved into L. I. S. along the bottom.

TABLE VII. Rate of Accumulation of Heat in Calories x 10^{-4}/Cm^2/Sec below the 10, 20, and 30-M Levels.

Cruises	*Depth (m)*	*72–00 to 72–10*	*72–10 to 72–20*	*72–20 to 72–30*	*72–30 to 72–40*	*72–40 to 72–50*	*72–50 to 73–00*	*73–00 to 73–10*
2–3	10	25.0	23.9	18.1	17.8	19.7	16.4	19.5
	20	24.5	17.2	12.8	—	—	12.8	15.0
	30	23.1	9.7	—	—	—	—	—
3–4	10	44.4	36.5	25.4	20.0	20.7	21.8	22.5
	20	54.0	25.8	18.6	—	—	13.2	15.4
	30	51.9	15.0	—	—	—	—	—
4–6	10	24.0	25.6	18.6	16.8	18.9	18.2	19.4
	20	26.8	18.7	13.5	—	11.6	12.7	15.4
	30	25.9	10.4	11.0	—	—	—	—
7–8	10	−24.0	−18.7	−18.3	−18.7	−23.0	−21.7	−23.0
	20	−25.7	−18.4	−13.3	−9.3	−13.3	−14.7	−16.7
	30	−24.0	−9.0	−11.0	—	—	—	—
8–9	10	−67.9	−47.4	−34.8	−27.4	−31.6	−31.2	−41.6
	20	−56.7	−34.5	−25.7	−13.6	−19.3	−22.1	−24.3
	30	−55.0	−20.0	−22.1	—	—	—	−15.5

TABLE VIII. Coefficients of Vertical Eddy Conductivity in G/Cm/Sec.

Cruises	*Depth* (*m*)	*72–00 to 72–10*	*72–10 to 72–20*	*72–20 to 72–30*	*72–30 to 72–40*	*72–40 to 72–50*	*72–50 to 73–00*	*73–00 to 73–10*
2–3	10	7.5	5.1	3.0	2.7	3.2	1.7	1.7
	20	?	20.	34.	—	—	2.7	3.4
	30	?	17.	—	—	—	—	—
3–4	10	11.	8.1	4.8	5.3	3.4	2.2	2.5
	20	?	20.	17.	—	—	2.2	2.2
	30	74.	?	—	—	—	—	—
4–6	10	8.8	8.3	4.7	3.4	3.1	2.0	2.8
	20	?	18.	14.	—	1.7	1.6	2.0
	30	31.	10.	5.4	—	—	—	—
7–8	10	?	?	12.	20.	13.	12.	50.
	20	33.	?	9.4	12.	7.7	6.5	12.
	30	25.	?	10.	—	—	—	—
8–9	10	615.	83.	35.	15.	8.9	10.	82.
	20	37.	47.	25.	10.	9.5	7.1	12.
	30	30.	29.	23.	—	—	—	7.9

The existence of a few patently invalid results suggests that there may be considerable error in the rest of the calculations. However, in general the variability in the results is consistent with oceanographic concepts. The coefficients were smaller in summer than in winter, which is presumably a stability effect. But the stability is not great at any time in L. I. S., nor are the eddy coefficients as small as the values that have been derived in more stable waters (cf. Sverdrup, et al., 1942: 484). The coefficients tend to increase toward the eastern end of L. I. S. It is suggested that this is due to the increasing tidal current, which probably is the major factor in the generation of turbulence in these waters. There are also two depth relations. First, the eddy coefficient is greatest at 10 m and least at 30 m except in certain cases in which the stability changes markedly with depth. Second, at any given depth the coefficient is least when the depth of the underlying water column is small, as in the central part of L. I. S. between 72° 30′ and 73° 00′ W. The effect of bottom friction on current velocity is a possible explanation of this result.

A cursory examination was made of coefficients of vertical eddy conductivity in B. I. S. for comparison with L. I. S. and for use in later analyses. Table IX lists the calculated values for the station that was previously used in the study of transport between the two Sounds. The calculations are based on the rate of change of the heat content below the depths listed in Table IX and upon temperature gradients averaged for 5-m intervals. Thus the gradient from 0–5 m was used to derive the value for the 2.5-m depth, etc. The last line of Table IX,

TABLE IX. Coefficients of Vertical Eddy Conductivity in B. I. S (Ca. 41° 10′ N, 71° 50′ W), 1946 Data.

Cruises	*2.5 m*	*7.5 m*	*12.5 m*	*17.5 m*	*22.5 m*	*27.5 m*
2–5	3.2	4.9	4.5	4.6	4.7	3.6
5–7	1.5	1.7	1.4	1.9	1.2	0.5
7–9	10.0	12.0	14.0	16.0	18.0	13.0
9–2	9.0	11.0	12.0	12.0	12.0	8.0

representing the midwinter period, is based on the assumption that the temperature cycles repeat from one year to the next with sufficient precision to warrant combining data from different years.

The central part of B. I. S. was examined on 13 occasions from January 11 to December 19, 1949. One to five bathythermograms and surface thermometer readings were taken each time, and the data were used to derive coefficients of vertical eddy conductivity. It was found that the gradients were small and variable in the surface layer in summer and in the whole vertical column in winter. Since it was intended to apply the results to a later analysis of oxygen and phosphate distribution, it seemed advisable to obtain a simplified and generalized set of data on eddy conductivity. Therefore all winter observations were combined into an average temperature gradient, and all summer observations in the upper 10 m were similarly combined. The remainder was averaged at 10-m intervals for each date. These simplified gradients were applied to the average temperature change in the preceding and following time interval, and the coefficients so obtained are shown in Table X. These differ only in minor details from the estimates previously shown in Table IX.

TABLE X. Coefficients of Vertical Eddy Conductivity in B. I. S., 1949 Data.

Date	*5 m*	*15 m*	*25 m*
19/XII, 11/I—24/II	11.0	7.0	2.0
24/III	9.0	5.0	2.0
9/IV	2.5	5.0	2.0
7/V	2.5	1.9	1.5
2/VI	2.5	1.6	2.9
9/VIII	2.5	0.5	0.7
28/VIII	2.5	1.0	0.7
17/IX	2.5	2.9	0.5

CURRENTS AND SALINITY DISTRIBUTION IN BLOCK ISLAND SOUND

Fig. 10 shows that surface water moves westward into B. I. S. between Point Judith and Block Island, traverses most of B. I. S., and then joins the southeasterly flow from L. I. S. The discussion of exchange between the two Sounds has indicated that some of the water entering B. I. S. continues as a subsurface drift into L. I. S. The average mass transport might be as much as 7,500 m³/sec (mean of values in Table IV) or it might be only a third as much (from estimates of the relative importance of advection and diffusion). These figures provide a rough estimate of current velocities in the deeper water. If the estimated transport occupied half of the cross section of B. I. S. at the longitude of the station used for analysis, the mean velocity would be 0.7–2.0 cm/sec.

A more detailed analysis of the currents may be obtained from an examination of the salinity distribution. Three stations were chosen for this purpose. The first was east of Block Island (ca. 41° 10′ N, 71° 12′ W). The second was the station previously used for studies of the exchange between the two Sounds, and the third was located in the eastern part of L. I. S. The three stations lay nearly in line along an east-west axis that approximately corresponds with the postulated direction of flow of the major current system. An equation was written to describe the rate of change of salinity S at a given point on this axis:

$$\frac{\partial S}{\partial t} = \frac{A_x}{\rho} \cdot \frac{\partial^2 S}{\partial x^2} + \frac{\partial}{\partial z} \cdot \frac{A_z}{\rho} \cdot \frac{\partial S}{\partial z} - V \frac{\partial S}{\partial x},$$

in which A_x and A_z are the coefficients of eddy diffusivity along the horizontal x-axis, directed positively eastward, and the vertical z-axis directed downward, and V is the horizontal current velocity. In applying the equation to estimate the currents at the center station, the following assumptions are proposed.

(1) The effect of lateral diffusion and advection at right angles to the x-axis is assumed to be negligible. This is probably false, but the necessary data for including the third axis are not available.

(2) The coefficient of lateral eddy diffusivity is designated as 3×10^6 g/cm/sec throughout, a value essentially in agreement with the L. I. S. estimates and probably of the right order of magnitude for B. I. S. (also cf. p. 63).

(3) The coefficients of vertical eddy diffusivity are assumed to equal the conductivity coefficients in Table IX.

The equation was applied in the form of finite differences. The methods were the same as those used in previous analyses that have been described in detail, and therefore the procedures will not be

TABLE XI. Estimated Current Velocities in B. I. S. (41° 10′ N, 71° 50′ W). Positive Values Are Easterly, Negative Westerly.

	10 m	*20 m*	*25 m*	*Mean*
March–July	0.2	0.3	−3.0	−0.57
July–October	−0.5	−0.5	−0.6	−0.53
Oct.–Jan. .	6.4	5.6	−32.0	−3.4
Jan.–March	−1.5	6.5	−8.4	−1.2

tabularized. The results are shown in Table XI. They confirm the existence of a westerly flow in the deeper water. The velocity seems to vary greatly, but part of this may be due to errors of sampling or of assumptions. The October to January period is particularly open to suspicion. During the remainder of the year, mass transport estimates developed from these velocities would be of the order of magnitude of the requirements for exchange between the two Sounds.

Table XI also indicates an easterly movement in the upper waters during most of the year, which presumably is part of the L. I. S. outflow. However, the eastward flow is weak; the average velocities for the water column as a whole (last column) are westerly. This agrees with previous evidence that most of the L. I. S. outflow passes out near Montauk Point and has relatively little effect on the central and eastern part of B. I. S.

The calculations suggest that the current pattern varies during the year. While the methods are such that not much confidence can be placed in the details of the analysis, certain aspects of the variability agree with other oceanographic information.

The period from July to October was the one time of the year when there was no evidence of any eastward transport through the central part of B. I. S. Freshwater drainage and the calculated L. I. S. outflow were smaller than average. Moreover, the lateral density gradient between the eastern part of L. I. S. and the center of B. I. S. was slightly stronger than at any other time of the year, largely because of the higher temperature of L. I. S. in summer. These phenomena logically would limit the outflow to a small and compact density current around Montauk Point. Finally, the plankton studies that follow will show that B. I. S. during this period had a greater than average abundance of organisms of offshore origin. This is part of a general phenomenon, for Bigelow and Sears (1939) have reported a maximum offshore influence in late summer and autumn in the whole coastal area. However, a vertically diffuse westerly drift of the kind shown in Table XI appears to be particularly favorable for bringing these organisms into B. I. S.

The L. I. S. outflow increased in midwinter, and it had a pronounced freshening effect on B. I. S. The outflow continued to be strong through the spring months, although the freshening effect lessened. Therefore, although the outstanding characteristic of the midwinter period was the magnitude of the L. I. S. influence, this was due primarily to the diffuse nature of the circulation pattern rather than to the volume of the outflow. While Fig. 3 indicates that most of the outflow passed around Montauk Point, as in other seasons, the major gradients in temperature and salinity were pushed eastward to the middle of B. I. S., and the density gradients were weaker than in summer. In the central and eastern part of B. I. S., about two-thirds of the winter stations showed a salinity minimum at mid-depths. Similar minima were observed also during the winter of 1949. These minima indicate that the effect of the L. I. S. outflow was most pronounced at mid-depths. In the zone of active admixture of the two water masses, there are areas, particularly in the northwestern part of B. I. S., where such admixture can produce water that is slightly fresher and colder than the main body of B. I. S. water but within the same density range. There are no density barriers to prevent this water from moving eastward through B. I. S. The quantitative analysis of the January–March period in Table XI indicates that this mid-depth movement is a definite current rather than lateral diffusion.

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Contribution No. 579

PHYTOPLANKTON OF BLOCK ISLAND SOUND, 1949

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ABSTRACT

Observations were obtained in the central part of Block Island Sound[2] on 12 occasions during 1949. They consisted of the following: measurements of temperature with surface bucket thermometer and bathythermograph; analyses of salinity, oxygen, and phosphate at a series of five or six depths between surface and bottom; phytoplankton cell counts at the same depths and analyses of plant pigments in the surface water; Secchi disc readings; collections of zooplankton and bottom fauna, which will be described by other writers.

Minimum concentrations of phytoplankton were found in midwinter and in midspring. There was a flowering of moderate size in February and other flowerings of slightly smaller proportions in the summer. The phosphate concentration had a midwinter maximum and declined sharply during the spring flowering. These phenomena are typical of temperate coastal waters.

The phosphate concentration was not at any time much less than 0.5 mg-at P/m^3, and the quantity of zooplankton was not correlated in an obvious way with the phytoplankton concentration. Probably neither of these factors was very important in determining the form of the seasonal cycle of phytoplankton. There was some

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[1] Contribution No. 579 from the Woods Hole Oceanographic Institution.

[2] Hereafter Block Island Sound will be referred to as B. I. S., Long Island Sound as L. I. S.

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evidence that the phytoplankton was partly controlled by undetermined chemical or biological factors; however, it also seems likely that physical oceanographic processes had a drastic effect on the quantity and composition of the flora.

The species composition is described and discussed from the standpoint of dominant species, seasonal succession, and comparison with adjacent waters. A few growth experiments during the period of the spring flowering provided information on the potential growth rates of the dominant species. In two of the three experiments, the growth rates were correlated with the observed growth in B. I. S. waters.

A quantitative analysis of oxygen and phosphate distribution has been used as the basis for a rough estimate of productivity. The average rate of increase of the phytoplankton in the upper 20 m is estimated to be of the order of 26% of the population per day, in excess of the immediate requirements of zooplankton and bacteria in the surface layer. The average consumption by zooplankton is probably not more than 4% of the phytoplankton population per day; bacterial requirements have not been estimated. Some of the excess phytoplankton production of the surface layer is transferred downward and is utilized by animals and bacteria on and near the bottom. The calculations indicate that not more than 19% of the phytoplankton population is so utilized each day. It is postulated that the remaining 7% of the daily excess production is lost by lateral dispersal (exchange with sparser populations offshore). The productivity estimates and the available data on phytoplankton distribution are used to determine the magnitude of the coefficient of lateral eddy diffusivity necessary to produce the estimated amount of physical dispersal. The result agrees with previous calculations of eddy diffusion obtained by analyzing the salinity distribution.

ACKNOWLEDGMENTS

The B. I. S. collections described herein were obtained aboard the commercial dragger Eleanor of Stonington, Connecticut. To the owner and master, Captain Ellery Thompson, the writer is deeply grateful, not only for permission to use the vessel and for help in every phase of the field work, but also for much useful information about B. I. S. and a thoroughly enjoyable association.

The phytoplankton survey was part of a cooperative program. Georgiana B. Deevey (1952) discusses the zooplankton collections; at a later date Frederick E. Smith will publish an analysis of the bottom fauna. To the former, the writer is indebted for permission to use some of the zooplankton data in the present paper, to the latter for help in the field work, and to both for valuable discussions of our various problems. Other members of the laboratory, Daniel Merriman, E. F. Thompson, and Y. H. Olsen, have been helpful in many ways.

The paper summarizes some hitherto unpublished observations on L. I. S. This work was made possible by the cooperation of Victor L.

Loosanoff of the Milford Laboratory of the U. S. Fish and Wildlife Service, who provided collecting facilities and laboratory space. This opportunity is taken to thank him and his staff for their help.

METHODS

On 12 occasions during 1949, samples were obtained from the central part of B. I. S. at either Station A or B (Fig. 1). The collections for phytoplankton counts and chemical analyses ordinarily consisted of five or six samples between surface and bottom. Other observations included a surface temperature reading with a bucket thermometer, a bathythermogram, a Secchi disc reading, and oblique tows with a Clarke-Bumpus sampler, using no. 2 and no. 10 nets. Additional surface samples and zooplankton tows were sometimes obtained at other positions indicated in Fig. 1.

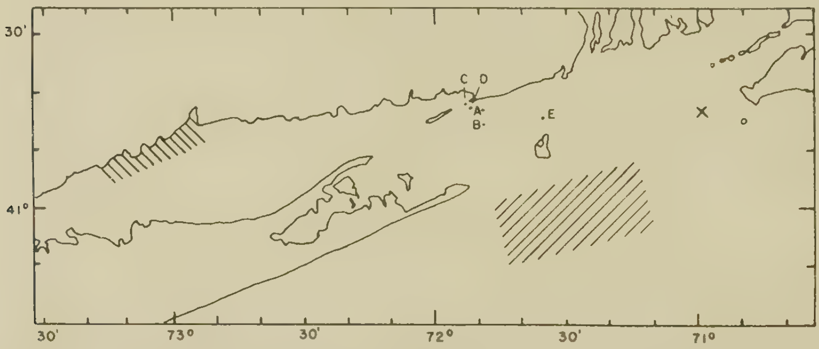

Figure 1. Positions of phytoplankton observations. A to E, stations in B. I. S.; x, Lillick's (1937) collections; hatched areas, previous measurements by the writer in L. I. S. and in the coastal water south of B. I. S.

Salinity samples were titrated with silver nitrate standardized against Woods Hole standard sea water. An ordinary burette was used. The probable error of the determinations is of the order of ± 0.03°/₀₀, which is considered to be sufficiently accurate for work in neritic waters.

Oxygen and phosphate were determined by the usual Winkler and Atkins-Deniges methods, respectively. A visual colorimeter was used to read the phosphates, and a salt error correction of 1.35 was applied throughout.

For phytoplankton examination 350 ml of water were preserved with neutral formalin. After the bottles had been allowed to stand several days, the samples were concentrated by slowly siphoning off the water until about 20 ml remained in the bottom of the bottle. This was quantitatively removed to a large vial. Later the sample was further concentrated to about 3 ml; the volume was measured and 1 ml was drawn off for counting in a Sedgwick-Rafter cell. At least one sample from each day's collection was prepared as a semipermanent Hyrax mount for identification purposes.

In addition to the counts, a liter of surface water was filtered through no. 50 Whatman paper, and the residue was extracted with acetone for colorimetric comparison with the Harvey plant pigment standard.

QUANTITATIVE ASPECTS OF THE PHYTOPLANKTON POPULATION

Plant Pigments. Fig. 2 illustrates the seasonal cycle of phytoplankton, as indicated by plant pigment determinations, together with some pertinent environmental factors. There was a midwinter minimum, a small and early spring flowering, and a moderately large population during the late summer. All these characteristics are common in neritic temperate waters.

The seasonal cycle of phosphate was also fairly typical, with its midwinter maximum and a severe decline during the flowering period. The midsummer concentration of phosphate was larger than that in many other areas described. It hardly seems likely that phosphate was a strongly limiting factor.

The zooplankton observations are discussed in detail by Deevey (1952). It suffices for the moment to say that no obvious relation exists between the quantities of phytoplankton and zooplankton. In particular, there is no evidence of an increase in zooplankton during and after the spring flowering, such as has been found in the English Channel and in various other localities. There is no clear evidence that zooplankton grazing controlled the size of the phytoplankton population at any time.

Cell Counts. Fig. 3 summarizes the total cell numbers in the surface water and the mean number of cells in the upper 20 m. The general form of the seasonal cycle resembles what has been described above, but the cell numbers are more variable than the plant pigment estimates. This variability is largely the result of differences in species composition. The largest numbers were obtained at times

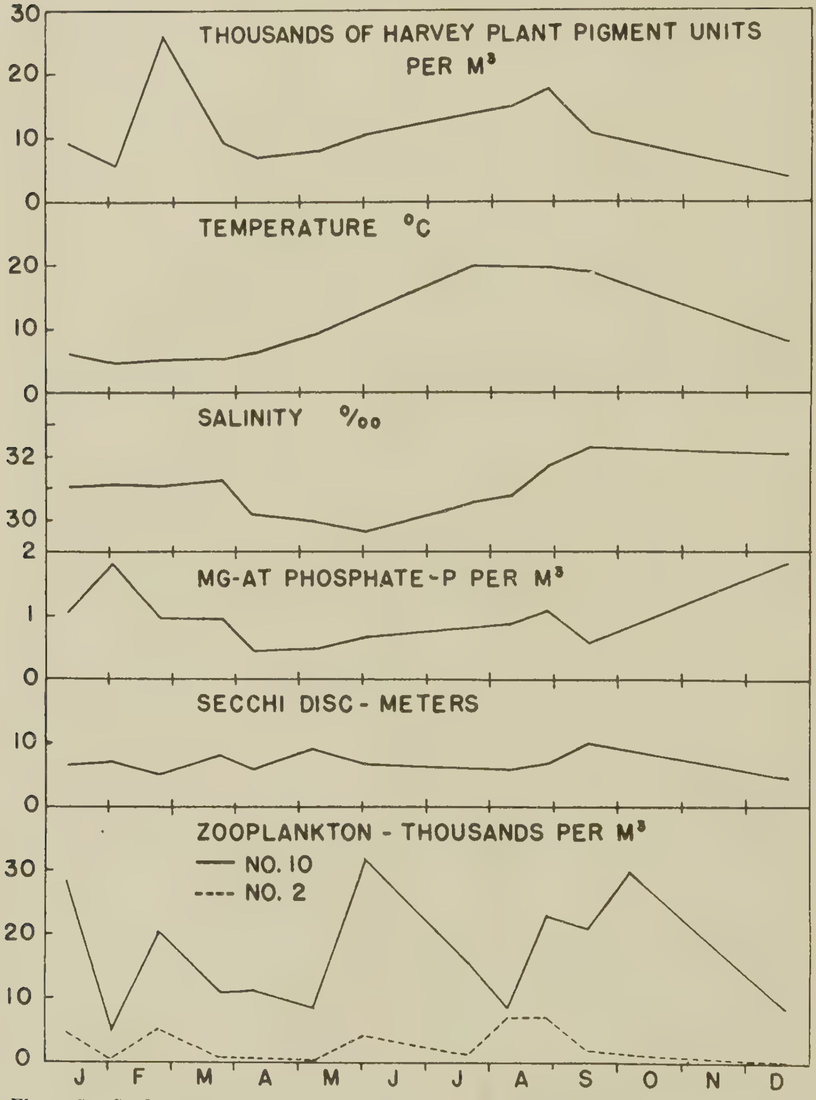

Figure 2. Surface measurements of plant pigments, temperature, salinity, and phosphate at Station A or B, transparency as determined by the Secchi disc, and the number of zooplankton organisms obtained by oblique tows with no. 2 and no. 10 nets.

when the population was dominated by small diatoms.

Fig. 4 shows examples of the three main types of vertical distribution that were found. The winter and early spring period of minimum

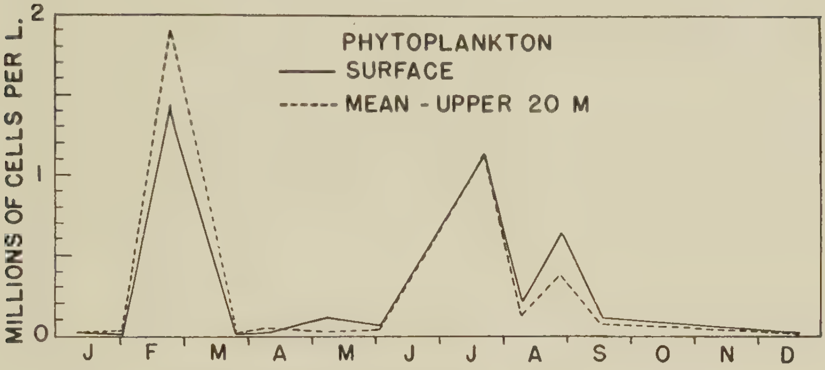

Figure 3. Seasonal variation in phytoplankton concentration at Station A or B.

stability was characterized by a population that increased with depth to a maximum at 10–20 m. After the onset of vernal warming, the population tended to decrease from the surface downward, except that in some cases there was another maximum in the thermocline.

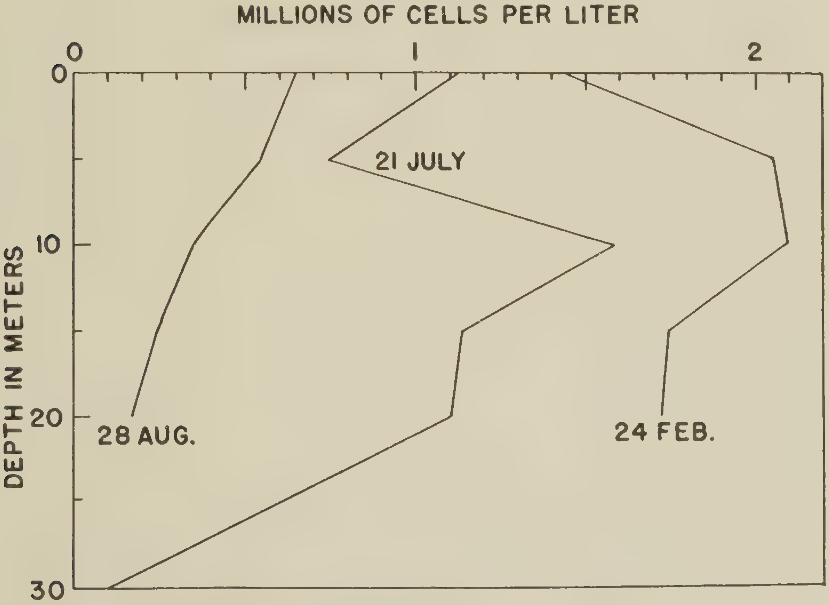

Figure 4. Vertical distribution of phytoplankton.

The surface and 5-meter cell numbers at stations A and B are compared in Table I with surface numbers at other positions previously designated in Fig. 1. There are two examples of extreme variability (E, January 11; B, May 7), but otherwise the cell numbers are fairly uniform, with perhaps slightly larger populations at the inshore stations C and D. In the surface water at station B, May 7, the population differed from the remainder of the water column in species composition as well as in quantity, and the salinity of the water was 0.3°/₀₀ higher than at 5 m. It is an obvious example of a water mass that differed in origin and history from the other water sampled on that date.

TABLE I. Thousands of Cells per Liter at Stations A to E in B. I. S.

Date	*meters*	*A, B*	*C*	*D*	*E*
11/I/49	0	22	20	—	132
3/II	0	10	73	45	31
	5	26			
24/II	0	1,442	2,051	1,448	1,623
	5	2,104			
24/III	0	16	52	63	22
	5	20			
7/V	0	117	18	14	—
	5	16			

Comparison with Adjacent Waters. In previous years the writer has obtained a few measurements of plant pigments in the coastal waters south of B. I. S. These are summarized in Table II. They average less than half the mean quantity in B. I. S. There is little information on the form of the seasonal cycle. A spring flowering has not been observed. In March 1947, one very large value of 56,000 Harvey units was obtained at a depth of 60 m at a coastal water station. It might have been a remnant of an earlier flowering of large proportions, but there is no certainty that the phytoplankton was of local origin. In August 1947, two stations near the edge of the

TABLE II. Surface Phytoplankton Concentrations Recorded As Harvey Units Per m³ in Waters 10–30 Miles South of B. I. S.

	Number of observations	*Mean Harvey units*
May 1939	2	2,500
March 1947	2	6,700
August 1947	2	5,000
December 1949	2	4,000

continental shelf had surface concentrations of 11,000 and 18,000 Harvey units, the order of magnitude of the summer population in B. I. S.

Lillick (1937) published an account of the phytoplankton population in the coastal waters near Vineyard Sound. While the area investigated was near shore in a depth of only 30 m, the temperature and salinity records indicate that it was more nearly typical of the open coastal waters of the region than is B. I. S. The seasonal cycle differed only in minor details from what has been described above, but the cell numbers were markedly less. The annual mean was of the order of 20,000 cells/l as compared with 325,000 in B. I. S. The comparison is biased by the fact that the latter flora was dominated by the small diatom *Skeletonema costatum*, while Lillick's data reveal relatively greater proportions of big diatoms. Excluding this one species, the annual mean in B. I. S. was about 45,000 cells/l.

In general, there seems to be little doubt that B. I. S. has a higher concentration of phytoplankton than the adjacent waters to the east and south, although the character of the data precludes any possibility of precise comparison.

The writer has obtained phytoplankton measurements of various sorts along the northern shore of L. I. S. in depths of 20 m or less. A nearly complete seasonal cycle was obtained between September 1938 and August 1939 (Riley, 1941). It was found that it consisted of an early winter minimum, a very long and intense spring flowering lasting from mid-January to April, other flowerings of smaller size in late summer, and a relatively smaller but by no means impoverished flora the remainder of the year. The phytoplankton was measured as milligrams of chlorophyll per m^3. According to a later series of measurements, one milligram of chlorophyll in the L. I. S. summer plankton is equivalent to about 3,100 Harvey units of plant pigments. Applying this conversion factor to the 1938–39 data yields the estimates of abundance shown in the first line of Table III. Subsequent measurements by the Harvey method are summarized in the remainder of Table III.

TABLE III. Plant Pigment Measurements (Harvey Units per M^3) in the Surface Water in the North Central Part of L. I. S.

	Maximum	*Minimum*	*Mean*	*No. of obs.*
September 7, 1938–August 18, 1939	ca 194,000	ca 16,000	ca 55,600	65
July 8–November 13, 1940	125,000	7,500	45,200	54
June 16–September 22, 1941	79,000	18,000	45,600	51
May 17–July 26, 1950	75,000	12,000	31,500	9

Cell counts were made during the summer of 1941. The total quantity varied from 60,000–7,400,000 cells/l, with a mean of 1,630,000. The routine counts did not include naked flagellates and other small forms. Occasional examination of freshly preserved material revealed 10–16 millions of these small cells per liter.

The small area that has been studied probably is not typical of L. I. S. as a whole. A few measurements in the central water mass have yielded smaller concentrations than those of the inshore waters represented by Table III. The concentration presumably declines toward the east. Station C (Table I) lies within the boundary of Fishers Island Sound and is subject to strong L. I. S. influence on the ebb tide. However, it more nearly resembles B. I. S. than the central part of L. I. S. with respect to phytoplankton concentrations. The population in the richer parts of L. I. S. appears to be an order of magnitude larger than that in the outer coastal waters. The B. I. S. data represent an intermediate point in what is probably a general gradient of decreasing concentrations.

SPECIES COMPOSITION

The Dominant Species in Block Island Sound in 1949. Nine genera, listed in Table IV, constituted 98% of the total number of cells in the phytoplankton counts. The first column of Table IV is the number of dates (out of a total of 12) when the genus was included in the routine plankton counts. The methods were such that there was a

TABLE IV. Summary of Dominant Genera and Species.

	No. of dates present	*Mean no. of cells per liter*	*% of total population*	*Maximum % of population*
Skeletonema costatum	12	270,500	83.5	99
Chaetoceros spp.	11	19,700	6.1	80
C. didymus	—	—	—	80
C. curvisetus	—	—	—	10
C. decipiens	—	—	—	12
C. compressus	—	—	—	13
Leptocylindricus spp.	8	6,900	2.1	45
L. danicus	—	—	—	40
L. minimus	—	—	—	5
Thalassiosira spp.	11	5,800	1.8	41
T. subtilis	—	—	—	41
Thalassionema nitzschioides	12	5,400	1.7	92
Nitzschia spp.	11	5,300	1.6	39
N. closterium	—	—	—	39
N. seriata	—	—	—	23
Asterionella japonica	10	1,700	0.5	7
Rhizosolenia spp.	12	1,500	0.5	11
R. faeroense	—	—	—	10
Guinardia flaccida	9	1,000	0.3	20

TABLE V. Seasonal Variation in the Species Composition of the B. I. S. Phytoplankton. An x Indicates That the Species Was Sufficiently Abundant to Be Found in the Routine Plankton Counts.

	Collection Dates											
	1/II	*3/II*	*24/II*	*24/III*	*9/IV*	*7/V*	*2/VI*	*21/ VII*	*9/ VIII*	*28/ VIII*	*17/ IX*	*19/ XII*
Skeletonema costatum	x	x	x	x	x	x	x	x	x	x	x	x
Thalassionema nitzschioides	x	x	x	x	x	x	x	x	x	x	x	x
Rhizosolenia setigera	x	x	x	x	x	x	x	x	x	x	x	x
Pleurosigma normanii	x	x	–	x	x	x	x	x	x	x	x	x
Distephanus speculum	x	x	x	x	x	x	x	x	x	x	x	–
Asterionella japonica	–	x	x	x	x	x	x	x	x	x	–	x
Nitzschia closterium	–	x	x	x	x	x	x	x	x	x	x	x
Guinardia flaccida	–	x	x	x	x	x	x	x	x	x	x	–
Melosira sulcata	–	–	x	x	x	x	x	x	x	–	x	x
Licmophora abbreviata	–	–	x	x	x	x	x	x	x	–	–	x
Ditylium brightwellii	–	–	x	x	x	x	x	x	–	–	x	–
Corethron hystrix	–	–	x	–	–	x	–	–	x	x	x	–
Leptocylindricus danicus	–	–	–	x	x	x	x	x	x	x	x	–
Actinoptychus undulatus	–	–	–	x	x	–	x	–	–	x	–	x
Rhizosolenia alata	–	–	–	x	x	x	x	x	x	x	x	x
R. hebetata f. *heimalis*	–	–	–	–	x	x	–	–	–	–	–	x
R. hebetata f. *semispina*	–	–	–	–	x	–	x	x	x	x	x	x
Nitzschia seriata	–	–	–	–	x	x	x	x	x	x	x	–

probability of more than 0.5 of recording a species if the average cell count was more than 20 per liter. The second column lists the number of cells per liter, averaged from the surface to 20 m and averaged for all collection dates. This number is next converted to a percentage of the total population. Finally the data for individual dates are used to determine the maximum degree of dominance at any one time, expressed as a percentage of the total population on that date.

Four of the genera were represented by a single species, as indicated. The remainder are given with a summary of the abundance of the genus as a whole, and in addition, individual species are listed if at any time they constituted as much as 5% of the total population.

Several other species were moderately important during a particular season, although in terms of mean annual cell numbers they did not warrant inclusion in Table IV. The following species at one time or another made up at least 5% of the population: *Ditylium brightwellii*, *Corethron hystrix*, *Melosira sulcata*, *Coscinodiscus subtilis*, and *Distephanus speculum*.

While the cell number is the most convenient criterion for examining population composition, certain other measurements might be used, no one of which would give precisely the same results. In terms of total cell contents, *Ditylium*, *Coscinodiscus*, and *Rhizosolenia* would be more important than is indicated by cell numbers. Conversely, the relative significance of the small diatoms would be reduced, although *Skeletonema costatum* would still be the dominant species.

Seasonal Cycles. *Skeletonema costatum*, *Thalassionema nitzschioides*, and *Rhizosolenia setigera* were present in every set of plankton samples. Six other species were present on at least nine of the twelve sampling dates. A total of 17 species, listed in Table V, were present on a broad seasonal basis and apparently were capable of tolerating almost the entire range of variability of the B. I. S. environment. Nevertheless, six of the species, in spite of their persistence, did not achieve a significant degree of dominance at any time.

Species of more transient occurrence are listed in Table VI in the order of their appearance throughout the year. Again the list includes forms that achieved a considerable degree of dominance and others that were present only as a few scattered cells.

Tables V and VI serve only to describe the most significant aspects of species occurrence and succession. As a species list, the data are incomplete. The material examined on prepared slides and during

TABLE VI. Seasonal Variation in the Species Composition of the B. I. S. Phytoplankton. An x Indicates That the Species Was Sufficiently Abundant to Be Found in the Routine Plankton Counts.

	Collection Dates											
	1/II	*3/II*	*24/II*	*24/III*	*9/IV*	*7/V*	*2/VI*	*21/VII*	*9/VIII*	*28/VIII*	*17/IX*	*19/XII*
Thalassiosira nordenskiöldii	x	x	x	x	x	x	–	–	–	–	–	–
Prorocentrum micans	x	x	x	x	x	x	x	–	–	–	–	–
Coscinodiscus excentricus	–	x	x	x	x	–	–	–	–	–	–	–
Biddulphia aurita	–	x	x	x	–	–	–	–	–	–	–	–
Peridinium spp.	–	x	x	x	x	x	–	–	–	–	–	–
Stephanopyxis palmeriana	–	–	x	–	–	–	–	–	–	–	–	–
Grammatophora marina	–	–	–	x	–	–	–	–	–	–	–	–
Rhizosolenia faeroense	–	–	–	x	x	–	–	–	–	–	–	–
Coscinodiscus centralis	–	–	–	–	x	–	–	–	–	–	–	–
Streptotheca thamensis	–	–	–	–	x	x	–	–	–	–	–	–
Thalassiothrix frauenfeldii	–	–	–	–	x	x	–	–	–	–	–	–
Thalassiosira gravida	–	–	–	–	x	–	–	–	–	–	–	–
T. rotula	–	–	–	–	x	x	x	x	–	–	–	–
Grammatophora angulosa	–	–	–	–	–	x	–	–	–	–	–	–
Striatella sp.	–	–	–	–	–	x	–	–	–	–	–	–
Chaetoceras brevis	–	–	–	–	–	x	x	–	–	–	–	–
C. decipiens	–	–	–	–	–	x	x	–	–	x	–	–
C. compressus	–	–	–	–	–	x	–	–	–	x	–	–
C. didymus	–	–	–	–	–	x	–	x	x	x	x	–
Dinophysis sp.	–	–	–	–	–	x	x	–	x	–	–	–
Ceratium lineatum	–	–	–	–	–	x	x	x	x	–	–	–
C. fusus	–	–	–	–	–	x	x	–	x	–	–	–
C. tripos	–	–	–	–	–	x	x	x	–	–	–	–
Lauderia borealis	–	–	–	–	–	x	x	–	–	–	x	–
Gonyaulax sp.	–	–	–	–	–	–	x	x	x	–	–	–
Rhizosolenia calcar—avis	–	–	–	–	–	–	–	x	x	–	x	–
Eucampia cornuta	–	–	–	–	–	–	–	x	x	x	x	–
Leptocylindricus minimus	–	–	–	–	–	–	–	–	x	x	x	–
Chaetoceros curvisetus	–	–	–	–	–	–	–	–	–	x	x	–
C. constrictus	–	–	–	–	–	–	–	–	–	x	–	–
Thalassiothrix longissima	–	–	–	–	–	–	–	–	–	x	–	–
Cerataulina sp.	–	–	–	–	–	–	–	–	–	x	–	–
Bacteriastrum delicatulum	–	–	–	–	–	–	–	–	–	–	x	x
Coscinodiscus subtilis	x	–	–	–	–	–	–	–	–	–	x	x
C. marginatus	–	x	x	x	x	–	–	–	–	–	–	x
Thalassiosira subtilis	–	–	–	–	–	–	–	–	–	–	–	x

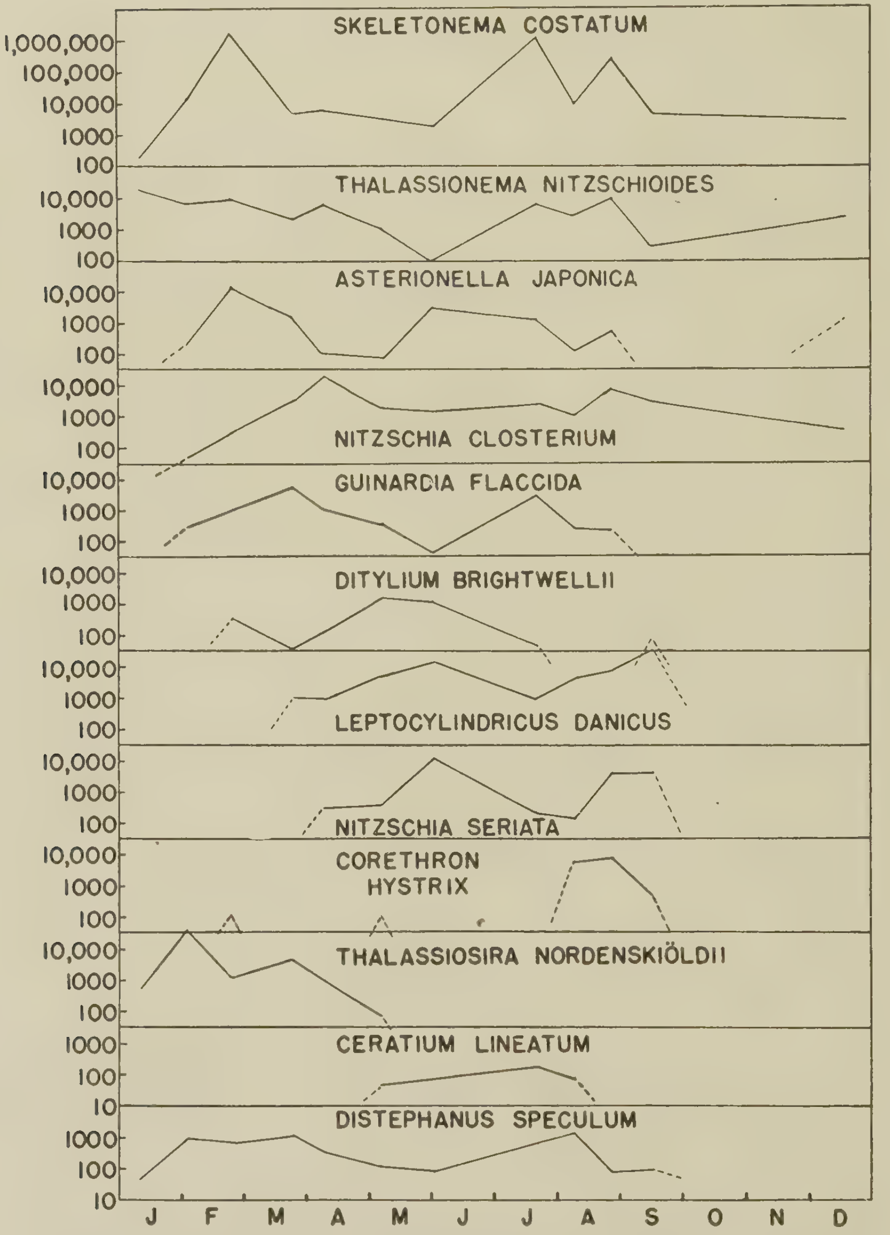

Figure 5. Seasonal variation of representative species of phytoplankton; the mean number of cells in the upper 20 m is plotted on a logarithmic scale.

the routine counts was the population occurring on each collection date in a volume of 150–500 ml of water. Examination of net tows and larger water samples presumably would increase both the size of the list and the period of occurrence of some species. Also, the writer was unable to derive satisfactory specific identifications for some of the forms. particularly when only a few specimens were available for study. It will be noted in Table IV that *Chaetoceros* and *Thalassiosira* spp. were present on 11 collection dates. The distribution of species indicated in Tables V and VI represents more limited periods of sufficient abundance to warrant identification by a nonspecialist. Similarly, most of the dinoflagellates are listed by genera.

Fig. 5 shows seasonal variations in abundance of some of the species. *Skeletonema* was so thoroughly dominant that its seasonal cycle differed little from that of the population as a whole (Fig. 3). More than half of the other persistent species also exhibited a tendency toward a bimodal seasonal cycle, with a maximum sometime between January and April and another during the summer. Some of these are illustrated in Fig. 5, together with representative examples of unimodal seasonal distribution.

Comparison with Adjacent Waters. Occasional examinations of net tows and water samples from L. I. S. indicate that *Skeletonema costatum* is the dominant species there as well as in B. I. S., at least during the spring and summer. Complete counts and species lists are not available for L. I. S. on a year-round basis. The comparison must be based largely on counts made during the summer of 1941. At that time *Skeletonema* averaged 1.2 million cells/l, or 72% of the total population, and reached a maximum concentration of 6.5 million cells/l in late summer. Other major constituents were *Thalassionema nitzschioides*, *Nitzschia closterium*, *Leptocylindricus danicus*, *L. minimus*, and *Asterionella japonica*. The only important species that was not found in the later survey of B. I. S. was a small *Rhizosolenia*, probably *R. delicatula*. Other *Rhizosolenia* and *Chaetoceros* spp. were found in about the same numbers in both Sounds, but were less significant percentagewise in L. I. S. The species in these genera were not fully identified during the L. I. S. survey, so that precise comparison is not possible.

For detailed comparison of B. I. S. with the waters to the eastward, the reader is referred to Lillick's (1937) work on the phytoplankton south of Vineyard Sound. It suffices here to say that the two floras are remarkably similar with the one major exception that *Skeletonema* was not excessively dominant in Lillick's counts.

GROWTH EXPERIMENTS

At the time of the spring flowering, a few simple experiments were performed to determine the reproductive capacity of the various species of phytoplankton. During the routine collection of samples for phytoplankton counts, a half-gallon bottle was filled with surface water, and at the end of the day's operations it was hung from a pier in Stonington Harbor just below low tide level. After three to seven days, formalin was added, and the phytoplankton was subsequently counted. Table VII shows the initial and final cell counts for the most important species and for the population as a whole in the first two experiments. From these counts the coefficient of increase k was determined according to the formula

$$k = \frac{\ln F - \ln I}{T},$$

where I and F are the initial and final cell counts, respectively, and T is time in days.

TABLE VII. Cell Counts and Growth Coefficients in Bottles of Surface Water.

	Feb. 2–5			*Feb. 24–Mar. 3*		
	Initial	*Final*	*k*	*Initial*	*Final*	*k*
Skeletonema costatum	2,780	110,000	1.23	1,340,000	3,750,000	.15
Thalassionema nitzschioides	5,200	17,200	.40	9,400	9,600	.003
Prorocentrum micans	780	500	−.15	100	1,100	.34
Thalassiosira nordenskiöldii	290	1,200	.48	53,500	32,500	−.07
Guinardia flaccida	290	500	.19	2,800	300	−.32
Distephanus speculum	120	1,000	.71	600	300	−.10
Coscinodiscus marginatus	40	800	.33	800	200	−.20
Asterionella japonica	100	1,300	.86	28,000	66,000	.12
Total cell count	9,600	135,000	.89	1,442,000	3,864,000	.14

The k values show that the population as a whole increased 89% per day at the time of the first experiment. Individual species varied widely in their reproductive capacity. During the period of February 2–24, a flowering developed in B. I. S. The average daily increase was 23% of the total population. Increases in individual species in B. I. S. were roughly proportional to their reproductive capacity at the beginning of the period, as indicated by the first experiment. This relationship is shown in Fig. 6A. However, the

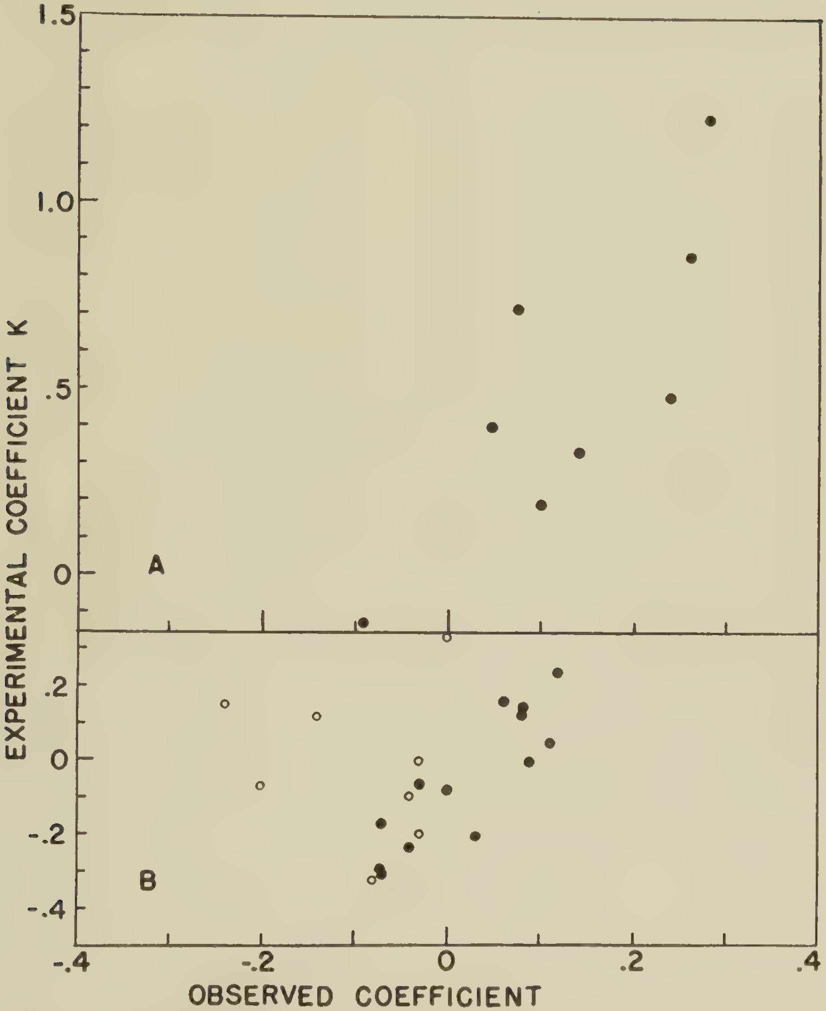

Figure 6. Coefficient of daily increase in cell number k in experimental bottles compared with the observed increase in B. I. S. *A*. Experiment of February 2 to 5. *B*. Circles, February 24 to March 3; dots, March 24 to 30. Each point represents a particular species.

experimental k's were higher than the observed coefficient of increase in B. I. S. This was to be expected, since the light intensity was higher in the experimental bottles than in the water column as a whole and since the phytoplankton was protected during the experiment from processes of physical dispersal.

TABLE VIII. CELL COUNTS AND GROWTH COEFFICIENTS IN THE EXPERIMENT OF MARCH 24–30. THE SURFACE WATER POPULATION OF APRIL 9 IS LISTED FOR COMPARISON OF EXPERIMENTAL RESULTS WITH SUBSEQUENT EVENTS IN B. I. S.

	Initial	*Final*	*k*	*April 9*
Skeletonema costatum	1,700	4,700	.17	4,600
Thalassiosira gravida	3,000	1,800	−.08	3,200
Nitzschia closterium	300	200	−.06	190
Peridinium sp.	600	100	−.30	200
Rhizosolenia alata	600	100	−.30	200
R. setigera	300	400	.05	1,800
R. faeroense	300	1,300	.24	2,100
Chaetoceros sp.	2,800	1,000	−.17	900
Guinardia flaccida	300	700	.14	1,000
Thalassionema nitzsch.	3,600	1,100	−.20	5,500
Coscinodiscus marginatus	400	100	−.23	200
Leptocylindricus danicus	300	600	.12	1,000
Ditylium brightwellii	100	100	.00	400
Total cell count	15,700	14,500	−.006	24,700

A third experiment, begun on March 24 (Table VIII, Fig. 6B), showed a similar relation between experimental reproductive coefficients and observed changes in the B. I. S. population. But in the second experiment, also plotted in Fig. 6B, there was no significant relation. All of the important species of February 24 declined during the subsequent month, irrespective of their reproductive capacity, and Table VIII shows that several other species joined the population. The most obvious explanation of the difference between this experiment and the others is that the water sampled on February 24 was swept away and replaced by another water mass with a somewhat different species composition.

CHEMICAL DATA

TABLE IX. SEASONAL AND VERTICAL DISTRIBUTION OF OXYGEN IN ML/L AND PHOSPHATE IN MG-AT P/M³

Depth	*Collection Date*										
m	*11/ I*	*3/ II*	*24/ II*	*24/ III*	*9/ IV*	*7/ V*	*2/ VI*	*9/ VIII*	*28/ VIII*	*17/ IX*	*19/ XII*
0	——	7.31	7.19	7.13	7.12	6.61	6.15	5.35	5.10	5.11	6.70
5	——	7.45	7.47	7.76	7.19	6.83	6.21	5.10	5.33	5.55	6.40
10	——	7.78	7.25	7.66	8.11	6.75	6.30	5.79	5.13	5.36	7.00
15	——	8.06	8.13	7.86	7.87	6.30	5.75	6.09	4.96	5.52	6.67
20	——	8.48	7.71	7.21	7.65	6.33	5.50	5.54	4.76	5.53	6.97
30	——	——	——	——	——	——	——	5.27	——	4.96	6.72
0	1.06	1.81	.98	.95	.45	.48	.67	.89	1.08	.58	1.84
5	——	1.39	.74	.83	.43	.48	.67	.80	.90	.53	1.71
10	——	1.93	.61	.90	.47	.52	.64	.87	.88	.57	1.63
15	——	2.29	.63	.90	.58	.48	.70	1.00	1.02	.57	1.71
20	——	1.52	.76	.93	.60	.50	.73	1.06	1.00	.62	1.71
30	——	——	——	——	——	——	.99	1.28	——	.72	1.84

Oxygen and phosphate determinations are shown in Table IX. Certain aspects of the data reveal the character of the biological agencies that affect oxygen and phosphate distribution. From February 24 to September 17 there was a mid-depth oxygen maximum at 5, 10, or 15 m, indicating that the production of oxygen by photosynthesis exceeded its utilization by the respiration of the whole biological association. During most of the year, the minimum phosphate concentration occurred between the surface and 15 m, suggesting net utilization by the population inhabiting the surface layer. Below 15 m the oxygen tended to decrease and the phosphate to increase with depth, indicating a predominance of katabolic processes in the lower water. As is commonly observed, there was a decline in the amount of soluble phosphate in the water column as a whole during the spring months, suggesting that phosphate regeneration did not keep pace with utilization.

Quantitative interpretation of these observations is uncertain because of the lack of detailed information on regional variations and because of the possible effects of currents and lateral mixing. Previous chemical observations in L. I. S. and in the offshore waters (Riley, 1939, 1941) suggest that the oxygen distribution is relatively uniform laterally. Probably there will be no great error if it is assumed that variations in oxygen are caused by local processes. Phosphate is not so easily generalized. There are no large differences between the Long Island and Block Island Sounds, but the phosphate concentration offshore tends to be less at the surface and greater in the bottom water. The effects of interchange between B. I. S. and offshore water are not easily predicted.

If advection and lateral diffusion are ignored, the rate of change of oxygen at a particular location is given by

$$\frac{\partial O^2}{\partial t} = \frac{\partial}{\partial z} \cdot \frac{A}{\rho} \cdot \frac{\partial O_2}{\partial z} + R\,,$$

in which A is the coefficient of vertical eddy diffusivity, z is the vertical axis, which is directed positively downward, and R is the biological rate of change of oxygen. The simplified determinations of eddy conductivity (Riley, 1952: table X) will be used as numerical values of A. Table IX provides the remainder of the data necessary for estimating the biological production and consumption of oxygen. The eddy coefficients were calculated for the depth ranges 0–10 m and

10–20 m, and the oxygen gradients will be determined for the same depths (in terms of finite differences). However, since the maximum oxygen concentration did not always occur at 10 m, it seems advisable to prepare two sets of estimates as follows: (a) The maximum observed concentration between 5 and 15 m is designated as the 10-meter concentration, and the derived biological rate of change will be called a maximum estimate. (b) The mean of the 5, 10, and 15-meter values will be called the 10-meter concentration, and the result will be regarded as a minimum estimate.

As a numerical example of the method of calculation, on April 9 the oxygen concentrations at 0, 10, and 20 m were respectively 7.12, 8.11, and 7.65 ml/l (for the maximum estimate). The calculated coefficients of eddy conductivity are 2.5 g/cm/sec between 0 and 10 m and 5 between 10 and 20 m. The rate of change of oxygen is determined from the preceding and following periods. The maximum concentration between 5 and 15 m declined from 7.86 ml/l on March 24 to 6.83 ml on May 7, a period of 44 days. Fitting these data to the equation,

$$\frac{6.83 - 7.86}{44 \times 86400} = \frac{1}{10^3}\left[\frac{5\,(7.65 - 8.11)}{10^3} - \frac{2.5\,(8.11 - 7.12)}{10^3}\right] + R\,,$$

$$-.3 \times 10^{-6} = (-\,2.3 - 2.5)\,10^{-6} + R\,,$$

$$R = 4.5 \times 10^{-6}\ \text{ml/l/sec}\,,$$

or 0.39 ml/l/day at a depth of 10 m. The calculation implies that oxygen is transferred downward through the 20-meter level and upward through the sea surface at rates of 2.3×10^{-6} and 2.5×10^{-6} ml/cm^2/sec, respectively. It is also apparent that the total excess of production over consumption in the surface layer is 4.5×10^{-6} ml/cm^2 of sea surface per second (0.39 ml/day). Furthermore, if lateral transfer can be ignored, the downward transport of oxygen must equal the biological utilization below 20 m; this amounts to 0.20 ml/cm^2/day, or about half of the excess in the surface layer.

Table X summarizes similar calculations for the whole year. Maximum and minimum values are determined according to the criteria cited previously. The results indicate that the net oxygen production during the period from February 3 to December 19 came to a total of between 34 and 102 ml/cm^2. Estimates of consumption in the bottom water ranged from 18–29 ml/cm^2. The latter are probably too low. A more detailed examination of the lowest part of the water column that was sampled, from 15–20 m, or from 20–30 m whenever possible, yielded a total of 41 ml/cm^2. This value, too, seems to be less than the excess produced in the surface layer. The calculations suggest that B. I. S. exists in a state of ecological imbalance, in which the production of phytoplankton exceeds its consumption.

TABLE X. Oxygen Production and Consumption in Milliliters per Cm^2 of Sea Surface per Day. The First Half of the Table Lists Maximum and Minimum Estimates of Production in the Upper 20 M in Excess of the Respiratory Requirements of the Biological Association. The Second Half Is the Calculated Consumption below 20 M

Date	*Production*		*Consumption*	
	Max.	*Min.*	*Max.*	*Min.*
3/II	.49	.01	−.25	−.43
24/II	1.16	.35	.25	−.05
24/III	1.02	.74	.44	.24
9/IV	.39	.14	.20	.03
7/V	.12	.03	.09	.05
2/VI	.14	.05	.11	.08
9/VIII	.17	.07	.03	.01
28/VIII	.10	.05	.05	.03
17/IX	.11	.08	.01	−.01
19/XII	.32	−.19	.02	−.18

The biological rates of change of phosphate were determined by the same kind of methods and will be summarized briefly, although, for reasons expressed previously, they are open to suspicion. The maximum estimate of phosphate utilization at 10 m was 0.15 mg-at P/m^3/-day, averaged for the entire period of the investigation, and the total utilization in the upper 20 m was 550 mg-at/m^2 of sea surface. Compared with the maximum oxygen estimate, the mean ratio of oxygen production to phosphate consumption is 231 : 1 by atoms. This figure can be regarded as approximately normal; however, estimates for individual dates varied widely. All 0 : P ratios for the period from February 24 to August 9 were above average, and the remainder were abnormally low. The mean for the spring-summer period was 510 : 1, and for the autumn-winter period it was 107 : 1.

DISCUSSION

In any area where a so-called seasonal cycle is observed, the changes from one sampling date to another are partly due to local ecological reactions and are partly the result of physical dislocation of the populations by transport and diffusion. The physical oceanographic survey has shown that there is continual transport of water through B. I. S. and a variable degree of admixture of the adjacent water masses. It is expected that the phytoplankton will be susceptible to significant physical effects. The present limited set of data cannot provide an adequate quantitative explanation of the observed seasonal variations of phytoplankton in terms of this interplay between ecological and physical oceanographic processes. However, the major features of the physical oceanographic influence can be clarified by brief analysis and discussion.

About 80% of the phytoplankton species and over 98% of the total number of individuals were typically littoral or neritic organisms. A few oceanic species were always present, but the only ones that achieved any degree of numerical importance were *Chaetoceros decipiens, Corethron hystrix,* and *Thalassiosira subtilis.* The number of individuals of presumably oceanic origin was greatest during the period from August to December and in the surface sample of May 7. On these occasions, salinity samples and other observations also indicated an oceanic influence. Thus there are numerous indications of excursions of oceanic water into B. I. S., although they appear to be less important quantitatively than the interchanges of adjacent neritic waters.

Among the neritic and littoral species there were some marked changes in composition and numbers from one sampling date to another. The most striking example is the vast fluctuations of *Skeletonema costatum* with respect to absolute numbers (Fig. 5) and degree of dominance. During the period from June to September it ranged from 3–98% of the total population. It has been mentioned before that this species is a dominant form in L. I. S. and is much less significant in the coastal waters to the east. Other important species such as *Asterionella japonica, Thalassionema nitzschioides,* and *Nitzschia closterium* appear to be more nearly uniform throughout the area. Probably *Skeletonema* can be regarded as an indicator of water mass exchange, although any such interpretation requires caution because this species has been known to produce flowerings in all of the nearby waters.

In the first two experiments described above, *Skeletonema* had a higher growth rate than any other species; in the third it was reduced to second place by *Rhizosolenia faeroense,* a transient species that attained a significant degree of dominance at this particular time. The experiments imply that *Skeletonema* is well adapted to live in B. I. S. Its removal or reduction may be generally indicative of the entrance of water masses from offshore, as in the period from February 24 to March 24 (cf. GROWTH EXPERIMENTS). It may then be reseeded by L. I. S. outflow; however, an increase of this species in B. I. S. cannot be regarded as evidence of a large influx of L. I. S. water unless other evidence shows that the observed increase is too large to be accounted for by ordinary growth.

TABLE XI. ESTIMATES OF PHYTOPLANKTON PRODUCTION IN THE UPPER 20 M (IN EXCESS OF UTILIZATION BY ZOOPLANKTON AND BACTERIA)

Date	*Phytoplankton*		*Production*	
	HU/m³	*Mg C/l*	*Mg C/l/day*	*%Phyt.*
3/II	5,700	.10	.066	66
24/II	26,000	.44	.20	45
24/III	9,100	.15	.23	153
9/IV	7,100	.12	.071	59
7/V	8,100	.14	.021	15
2/VI	10,800	.18	.026	14
9/VIII	15,000	.25	.032	13
28/VIII	17,700	.30	.021	7
17/IX	10,900	.19	.026	14
19/XII	4,100	.07	.016	23
Mean	11,200	.19	.050	26

The data on oxygen distribution provide a method of roughly estimating the rate of increase in the organic content of the phytoplankton population. The first two columns in Table XI list the surface concentration of phytoplankton as Harvey units per m³ and its estimated carbon content, the latter derived from the former by the application of an average conversion factor (cf. Riley, Stommel, and Bumpus, 1949). The next column is an estimate of average daily carbon production in the upper 20 m, obtained by applying the oxygen : glucose-carbon ratio to the average of the maximum and minimum estimates of oxygen production in Table X. The final column shows the calculated daily production as a percentage of the surface phytoplankton crop.

From the method of deriving these figures from observed oxygen concentrations, it is apparent that they represent the difference between phytoplankton production and the total utilization of organic matter *in situ*. Deevey (1952) indicates that the average consumption by zooplankton is at most about 4% of the phytoplankton crop per day; bacterial respiration has not been determined. Thus the average estimate for phytoplankton production is somewhat more than 30% per day.

Some or all of the excess phytoplankton production of the surface layer is removed to the deeper water and is oxidized there by bacteria and animals. The data in Table X and the accompanying discussion suggest that the utilization in the lower layer may be markedly less than the excess production of the overlying water. The calculations are obviously crude and not thoroughly dependable; nevertheless, the question arises as to whether it is reasonable for such an unbalanced ecological system to exist in B. I. S. The only likely alternative to complete biological utilization is lateral dispersal by physical means. It is generally recognized that the large concentrations of neritic localities must be subject to reduction by interchange with more sparsely populated offshore waters, but estimates have not been made of the magnitude of such losses.

In B. I. S., the mean quantity of phytoplankton as determined by the plant pigment method was more than twice the average of the available offshore observations. Both lateral diffusion and the transport of offshore water into the Sound would reduce its phytoplankton concentration. On the other hand, the B. I. S. population might be increased by the addition of L. I. S. water. But since the latter primarily influences the westernmost part of B. I. S., its effect will be ignored in the first approximation.

A simple problem is postulated as follows:

(1) Assume that within the ten-mile (1.8×10^6 cm) width of B. I. S. there exists a uniform concentration of 11,200 Harvey units per m^3, or about 190 mg of phytoplankton carbon per m^3, while ten miles to the south the concentration is 4,500 Harvey units (mean of the observations in Table II) or 76 mg of carbon.

(2) The offshore water is assumed to move into B. I. S. at a speed of 1 cm/sec. There is also a turbulent exchange which will be analyzed later.

(3) The excess production of phytoplankton in the surface layer is postulated to produce 68 ml O_2/cm^2/year (average of the maximum and minimum values in Table X), while the utilization of phytoplankton on or near the bottom results in the consumption of not more than 41 ml/cm^2/year. The difference between these figures is postulated to represent the production of phytoplankton that is lost from B. I. S. by physical dispersal. It corresponds to a production of 13

mg glucose-carbon/m^3/day in a 30-meter column of water, or 150×10^{-6} mg C/sec.

(4) The equation for the rate of change of the phytoplankton population is written

$$\frac{\partial P}{\partial t} = R + \frac{A}{\rho} \cdot \frac{\partial^2 P}{\partial x^2} - V \frac{\partial P}{\partial x},$$

where R is the biological rate of change of the phytoplankton concentration P, A is the coefficient of lateral eddy diffusivity, V is the current velocity, and x is lateral distance. According to the first assumption, the problem deals with a simplified steady-state distribution, such that $\partial P/\partial t = 0$. From the data that have been given, the equation may be written in terms of finite differences,

$$150 \times 10^{-6} + \frac{A}{\rho} \frac{(76 - 190) - (190 - 190)}{(1.8 \times 10^6)^2} - \frac{(-1)(76 - 190)}{2 \times 1.8 \times 10^6} = 0,$$

$$A = 3.3 \times 10^6 \text{ g/cm/sec}.$$

This value of the lateral eddy coefficient agrees closely with estimates derived in the previous paper (Riley, 1952) from examination of the salinity distribution. It indicates that the estimated average loss of phytoplankton (about 7% of the population per day) by physical processes is credible. However, two phases of the problem require further examination before the result can be fully accepted. One is the quantity of phytoplankton in the eastern part of L. I. S. and its effect on the B. I. S. population. The other is the question of the source and rate of supply of phosphate and other nutrients that must be transported into B. I. S. in order to replace the loss that occurs when these substances are carried away in organic combination in the plankton.

While the discussion has been mainly concerned with physical oceanographic factors, it is apparent from the experiments that the seasonal cycle is partly controlled by biological or chemical factors. Growth rates were high during the time when the spring flowering was developing; later they became much lower. The change cannot be accounted for by any of the observed environmental factors. However, the existence of reduced growth rates in the experiments subsequent to the flowering is sufficient evidence that the population was kept at a low level by physiological limitations as well as by physical dispersal.

Field observations yield little information about the nature of the ecological control of the population. The minimum phosphate concentration was larger than is ordinarily the case in either L. I. S. or in the offshore waters. It seems unlikely that phosphate was an important limiting factor. Nevertheless, the abnormally large ratios of oxygen production to phosphate utilization in spring and summer indicate that the phosphate uptake declined even though there was a large quantity available. Possibly this phenomenon can be explained in terms of the availability of other essential nutrients, but at the moment the reason remains obscure.

The previous discussion has indicated that removal of phytoplankton by zooplankton grazing is less significant than physical dispersal. These two phenomena are closely related. If grazing were more important, so that it reduced the phytoplankton crop to the same concentration as that in the offshore waters, the exchange would cause no net loss of phytoplankton from B. I. S. The fundamental problem is the reason for the inability of the animal population to consume the phytoplankton as rapidly as it is produced. The zooplankton investigation in a future paper of the series is a necessary prerequisite to a discussion of this problem.

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Contribution No. 581

PHYSICAL FACTORS AFFECTING THE DISTRIBUTION OF EUPHAUSIDS IN THE NORTH ATLANTIC

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Woods Hole Oceanographic Institute

CONTRIBUTION NO. 68
The Marine Laboratory, University of Miami

PHYSICAL FACTORS AFFECTING THE DISTRIBUTION OF EUPHAUSIDS IN THE NORTH ATLANTIC[1]

HILARY B. MOORE
The Marine Laboratory, University of Miami

Abstract

A theoretical relationship has been developed between the environmental temperature and the survival index of a planktonic organism. The significant temperatures are the degree of departure from the optimum values of surface temperature (T_S) and temperature at the depth of 10^{-12} illumination (T_{I-12}). Allowance is included for cases where the optimum is closer to the upper than to the lower limit of tolerance, and also for a degree of physiological adaptation. It is considered that the survival index of a species in a given habitat should be reflected approximately in the relative abundance in that habitat of the species in question among the total population.

The geographical distribution of Euphausids in a considerable part of the North Atlantic and Mediterranean is charted. Charts are also given, for the same area, of the distribution of the extinction coefficients of the water and of the calculated values of T_{I-12}. The relation of the abundance of each of the commoner species to T_S and T_{I-12} is given.

A good agreement is found between theoretical and observed temperature relationships if it is assumed that, for most species, there are two different temperature optima, one associated with the day level and the other with the night level. The likelihood of such a dual temperature control is discussed.

For a few species, critical temperatures as indicated by scattering layer records are compared with those indicated from geographic distribution. Finally, for *Euphausia hemigibba,* the geographic distribution, as predicted from physical conditions, is shown to agree reasonably well with actual observations.

Introduction

In a previous paper (Moore, 1950) it was shown that the diurnal migration of Euphausids is primarily influenced by illumination, with temperature as a modifying influence during part of the cycle. In an area such as the Mediterranean, where there is little thermal stratification of the water, their movements as deduced from the records of the scattering layer, tend to maintain them throughout the daylight hours at a constant illumination. In the stronger thermal stratification of the Atlantic, their morning descent carries them down through a greater temperature range. Correlated with this condition, their de-

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scent follows the changing illumination for its first period, but beyond a certain depth, descent ceases, despite the now increasing illumination. This level is maintained throughout the midday period until a time in the afternoon when the decreasing illumination takes control again, and the evening ascent is commenced. That temperature is the factor concerned is indicated by the dependence of the depth at which this "noon flattening" of the migration curves occurs on local temperature distribution.

It was postulated that the temperatures encountered at the vertical extremes of the diurnal migration were limiting factors in the geographical distribution of a species, and it was shown that the distribution of these two temperatures was adequate to explain the distribution of the commoner Euphausid species in the western North Atlantic. In the present paper, the effects of temperature are considered in greater detail, and the theoretical relationship arrived at is compared with observed Euphausid distributions. For the latter, a very much wider area of the North Atlantic has now been covered.

The author gratefully acknowledges the assistance, both with advice and in obtaining material and data, of the staff of Woods Hole Oceanographic Institution and the Marine Laboratory, University of Miami. In particular, Mrs. Andrew Bunker has carried out a large part of the abstracting and calculating as well as examining many of the plankton samples.

THEORETICAL CONSIDERATION OF TEMPERATURE EFFECTS

During the course of its diurnal migration cycle, an animal inhabits two widely different environments. Not only may these differ by as much as 10 or more degrees in temperature, but they differ also in phytoplankton content, oxygen concentration and other factors. The night environment is near the surface where the phytoplankton supply is rich. Too low a temperature here might be expected to result in decreased activity and lowered feeding rate. The same might be true of too high a temperature, and if the Euphausids avoided this by remaining at deeper and therefore cooler levels, their food supply would be less. Thus an optimum temperature may be assumed to exist for the night conditions. At the deeper day level the feeding rate is presumably much less. If at that level the temperature is too low, then the animal can only avoid it by enduring the greater illumination associated with higher levels. On the other hand, if the temperature is too high, then an impossibly extensive vertical migration may be

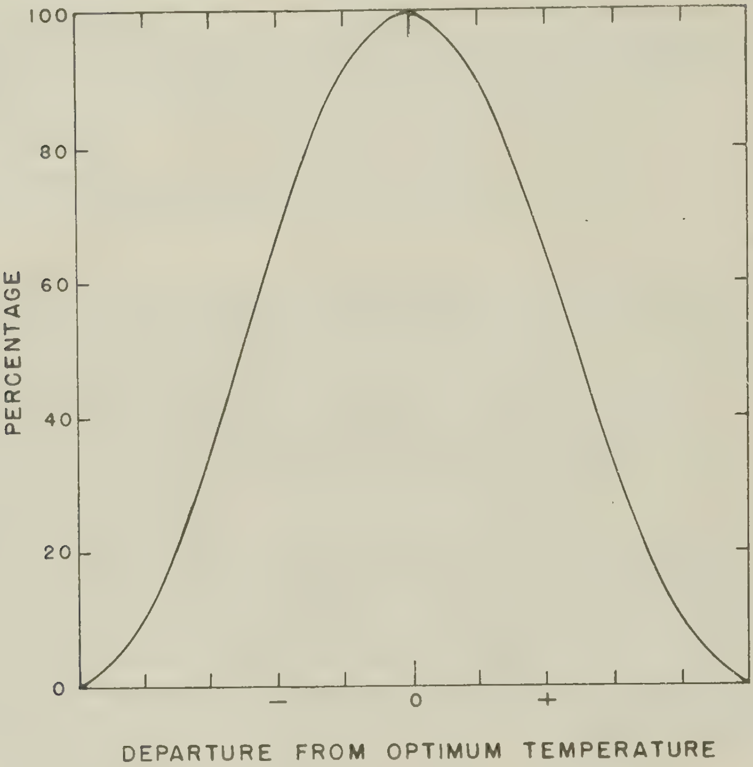


FIGURE 1. Hypothetical curve relating survival index to departure from optimum temperature. No temperature units are shown since these vary in different cases.

involved if sufficiently low temperatures are to be reached. Thus an optimum day temperature also is postulated.

The ability of an organism to survive, and the success with which it does this, is a highly complex process, dependent on various external and internal conditions. Fischer-Piette (1948) has discussed this, and has shown that the "prosperity" of the organism may be measured in many ways. The optimum environmental conditions vary considerably according to the aspect of this prosperity which is considered. In a later section of the present paper, the prosperity of the various Euphausid species will be assessed in terms of their abundance relative to one-another. Although this involves inter-specific competition, it is assumed that their ability to compete depends on the degree of suitability of other environmental conditions. Since the processes in-

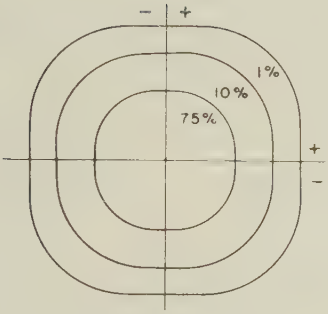


FIGURE 2.

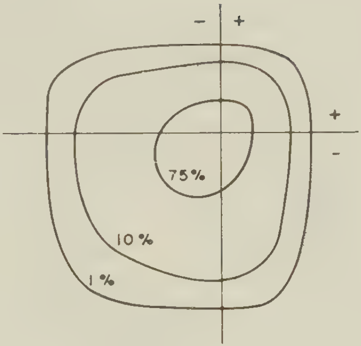


FIGURE 3.

FIGURE 2. Relation of survival index to departure from optimum temperature in a case involving alternation between two climates, in both of which there is a symmetrical response above and below the optimum.

FIGURE 3. As in Figure 2, but with an asymmetrical temperature response in which the lethal limit is further below than above the optimum.

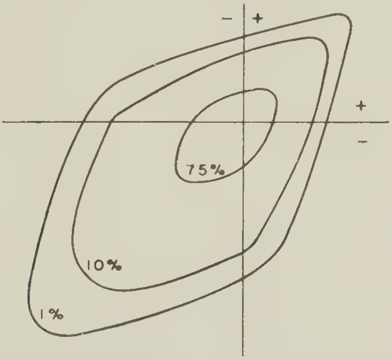


FIGURE 4. As in Figure 3, but involving physiological adaptation also.

volved are so little understood, the deliberately vague term "survival index" is used here. In considering the effects of temperature, this index is given a value of 100 per cent when optimum temperature conditions are present, and 0 per cent when conditions are beyond the tolerance range of the species.

Since considerable simplification of the problem is necessary, let us assume that there is a simple relationship between this survival index and temperature, and that this follows the limited section of a sine curve shown in Figure 1. Actual values are omitted from the temperature scale, since they will vary from one species to another and there is no implication that there is an actual sine relationship. Since two

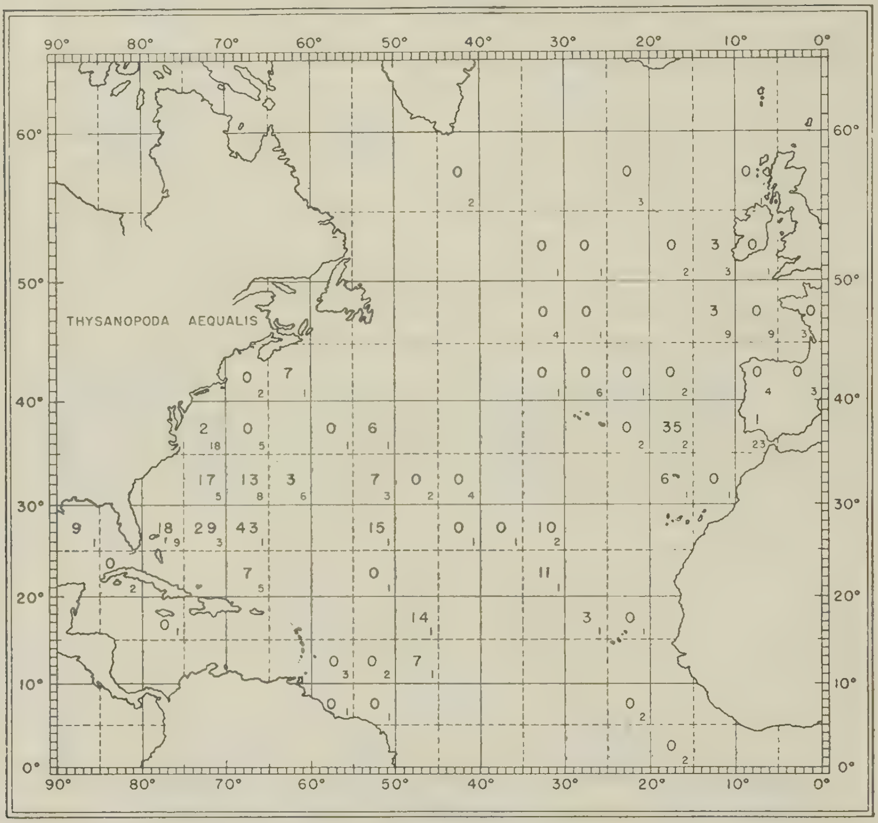

THYSANOPODA AEQUALIS
90° 80° 70° 60° 50° 40° 30° 20° 10° 0°
60° 50° 40° 30° 20° 10° 0°
0 2
0 3
0 1
0 1
0 1
0 2
3 3
0 1
0 4
0 1
3 9
0 9
0 3
0 2
7 1
0 1
0 6
0 1
0 2
0 4
0 3
2 18
0 5
0 1
6 1
0 2
35 2
1 23
17 5
13 8
3 6
7 3
0 2
0 4
6 1
0 1
9 1
18 9
29 3
43 1
15 1
0 1
0 1
10 2
0 2
7 5
0 1
11 1
0 1
14 1
3 1
0 1
0 3
0 2
7 1
0 1
0 1
0 2
0 2

FIGURE 5.

FIGURES 5-14. Geographic distribution of Euphausids expressed as the percentage of each species in the total Euphausid population (excluding the genus *Stylocheiron*). Values are averages for 5° squares, and the suffixes in Figure 5 show the number of samples available for analysis in each square.

different environments are involved in the diurnal migration cycle, the survival index for a species in a given locality will be a function of the degree of departure of both the day and the night level temperatures from the optimum temperature. For simplicity, it may be assumed that the overall survival index of the species for that locality is the product of the indices for day and night conditions, both of these being read from the curve given in Figure 1. Figure 2, therefore, represents the overall survival index for all possible relations of the day and night temperatures to the optimum temperature. Part of this

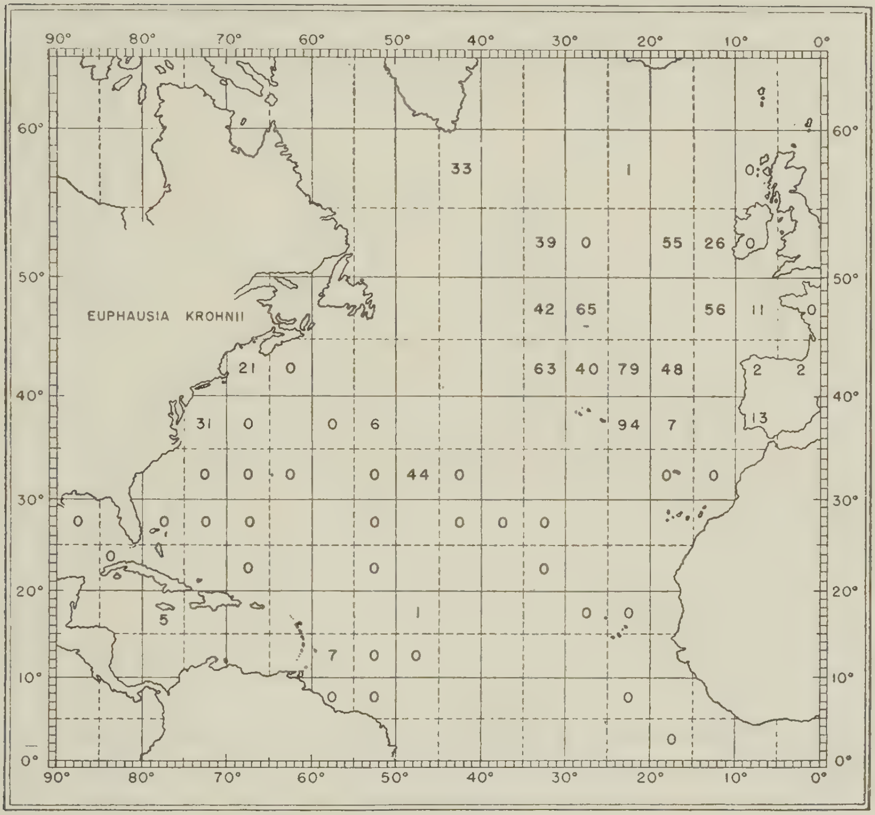

EUPHAUSIA KROHNII
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
60°
50°
40°
30°
20°
10°
0°
33
1
39
0
55
26
0
42
65
56
11
0
21
0
63
40
79
48
2
2
31
0
0
6
94
7
13
0
0
0
0
44
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
5
1
0
0
7
0
0
0
0
0
0

Figure 6.

array represents conditions which would be unlikely to be encountered under natural conditions, since the surface temperatures would have to be lower than the deep ones. This could occur only where the effect on density was compensated for by corresponding salinity differences.

For many organisms, the lower lethal temperature is further from the optimum than is the upper limit. It would therefore be better to modify the curve in Figure 1 to give a more extended scale on the left of the optimum. If this is done, a pattern of the type shown in Figure 3 is obtained for the relationship of survival index to two varying temperatures. A still further modification is called for to allow for the physiological adaptation which frequently occurs and may result in physiological races. This may be represented here by a shift of the optimum in Figure 1, the amount of the shift being a function

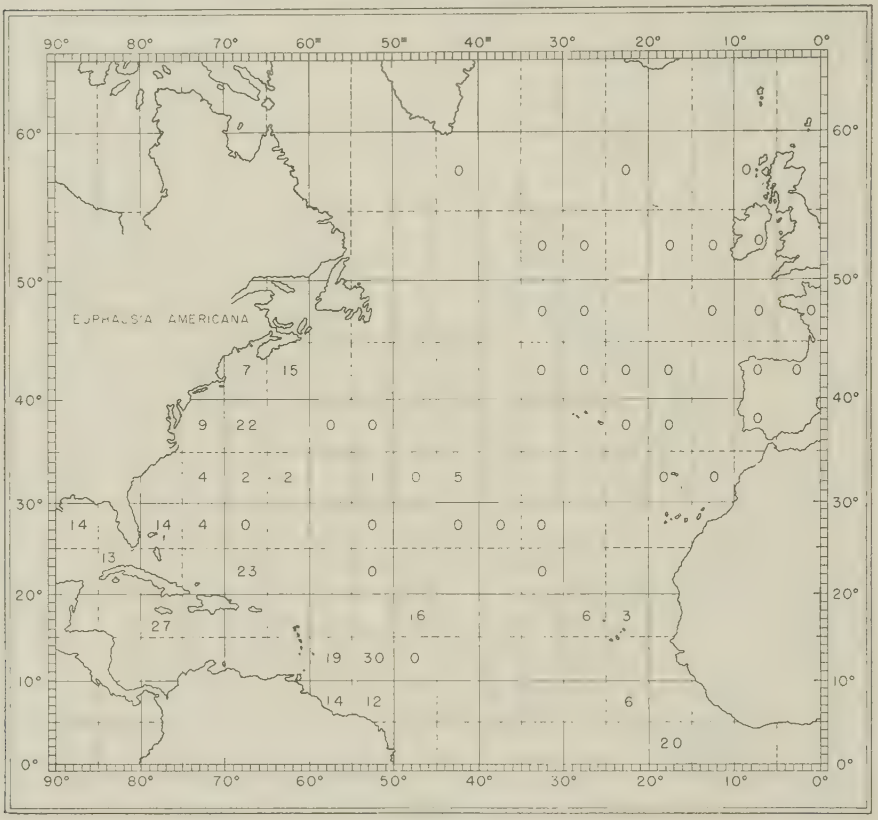

90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
60°
50°
40°
30°
20°
10°
0°
EUPHAUSIA AMERICANA
0
0
0
0
0
0
0
0
0
0
0
7
15
0
0
0
0
0
0
9
22
0
0
0
0
0
4
2
2
1
0
5
0
0
14
14
4
0
0
0
0
0
13
23
0
0
27
16
6
3
19
30
0
14
12
6
20

FIGURE 7.

of the average departure of the environment from optimum conditions. If an initial optimum value is assumed, then the adapted optimum may be considered as having shifted by half the mean of the departures of the day and night temperatures from the initial optimum. While based on arbitrary assumptions, this yields the required effect of a higher degree of physiological adaptation where both temperatures depart in the same direction from the initial optimum, and sets a limit to the extent of physiological adaptation possible. With maximum physiological adaptation, the survival index is 0 per cent when either of the two temperatures departs from the optimum by twice the maximum permissible unadapted departure. When such allowance for physiological adaptation is made, curves given in Figure 3 are modified to give the more elongate pattern shown in Figure 4.

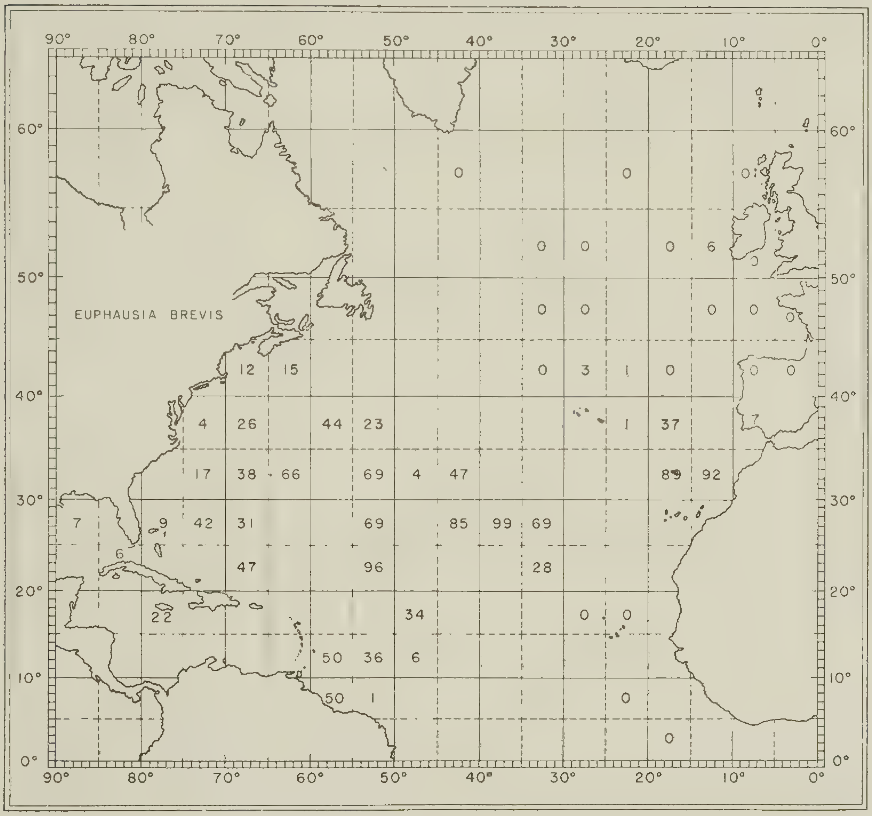

90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
60°
50°
40°
30°
20°
10°
0°
EUPHAUSIA BREVIS
0
0
0
0
0
0
6
0
0
0
0
0
12
15
0
3
1
0
0
0
4
26
44
23
1
37
7
17
38
66
69
4
47
89
92
7
9
42
31
69
85
99
69
6
47
96
28
22
34
0
0
50
36
6
50
1
0
0

FIGURE 8.

OBSERVED GEOGRAPHICAL DISTRIBUTION OF EUPHAUSIDS

Data on geographical distribution have been taken from all available published sources, together with samples taken by R. V. "Atlantis" and other vessels. Only those sources which provide numerical information on relative abundance have been included, and data from areas from which the necessary hydrographic data are lacking have been omitted. Unfortunately, the absence of information on transparency for the area has required the omission of much of the data given by Einarsson (1945). The same is true of the stations in the northern part of the Mediterranean, given by Ruud (1936). As in earlier work, the abundance of a species has been expressed as its percentage in the total Euphausid population at that place, but the

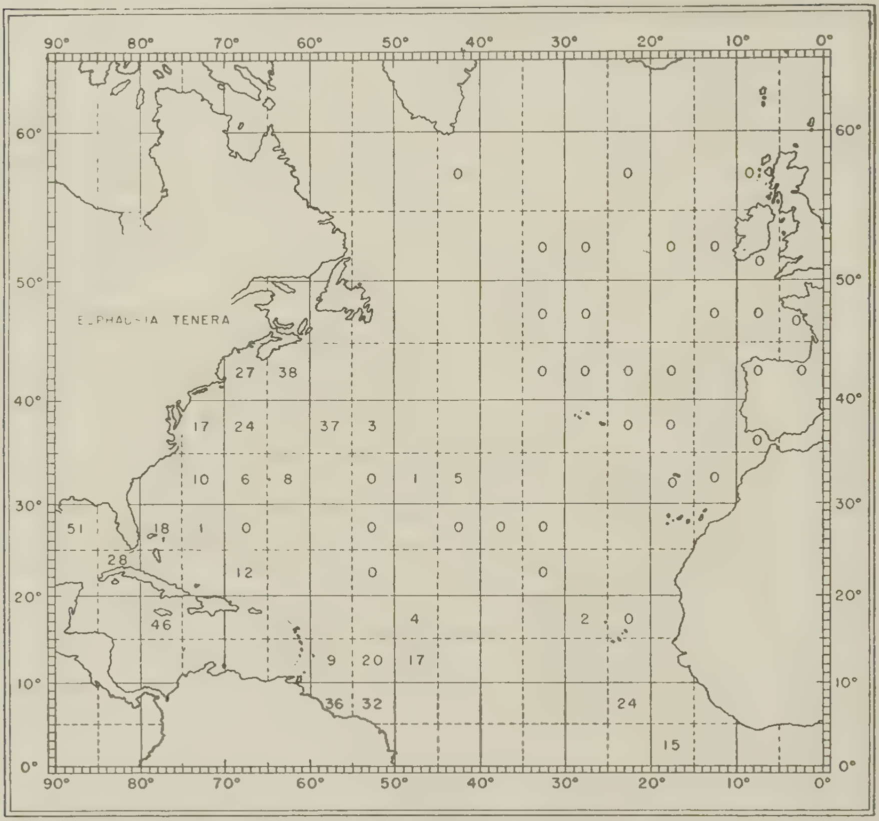

EUPHAUSIA TENERA
90° 80° 70° 60° 50° 40° 30° 20° 10° 0°
60° 50° 40° 30° 20° 10° 0°
0 0 0
0 0 0 0 0
0 0 0 0
27 38 0 0 0 0 0 0
17 24 37 3 0 0 0
10 6 8 0 1 5 0 0
51 18 1 0 0 0 0 0
28 12 0 0
46 4 2 0
9 20 17
36 32 24
15

FIGURE 9.

genus *Stylocheiron* has been omitted in the calculation of the latter. Various types of net hauls are included, and all are not of the same significance. Where a series was taken at a single station, their combined content has been treated as a single haul, but samples below about 500 fathoms have not been included. The fact that many of the "Atlantis" hauls were made at the surface at night, together with the reversed type of diurnal migration found in some species of *Stylocheiron,* justified the omission of that genus. The results for 10 of the most common species of the area are shown, averaged by 5° squares, in Figures 5-14. Since we are mainly concerned with the warm water species of the Atlantic, only one northern form, *Thysanoessa longicaudata,* has been included for comparison. In part of the area under consideration, such forms as *Meganyctiphanes norvegica*

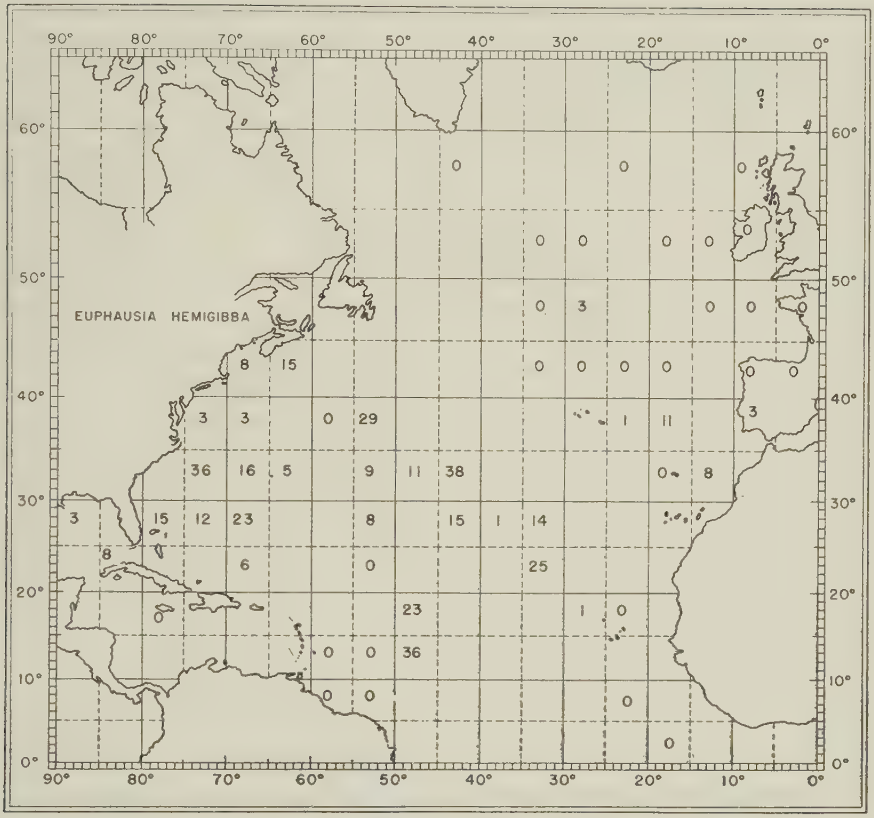

90° 80° 70° 60° 50° 40° 30° 20° 10° 0°
60°
50°
40°
30°
20°
10°
0°
EUPHAUSIA HEMIGIBBA
0 0 0
0 0 0 0
0 3 0 0 0
8 15 0 0 0 0 0 0
3 3 0 29 1 11 3
36 16 5 9 11 38 0 8
3 15 12 23 8 15 1 14
8
6 0 25
23 1 0
0 0 36
0 0 0
0

Figure 10.

are abundant. These have been omitted because they are northern forms, and, in this case, because their ability to live in shallower water than the typically oceanic species, complicates the picture. Dr. M. V. Lebour (*in litt.*) has suggested that the present *Thysanopoda aequalis* requires revision, and may prove to be composed of more than one species. Our results do not show any marked discontinuity of distribution or other characteristics, but such would not of necessity be expected. *Euphausia americana* and *E. krohnii* were, at one time, confused, but were adequately separated throughout the records utilized here. *Nematoscelis microps* has been included, but is subject to doubt as to the validity of some of the identifications.

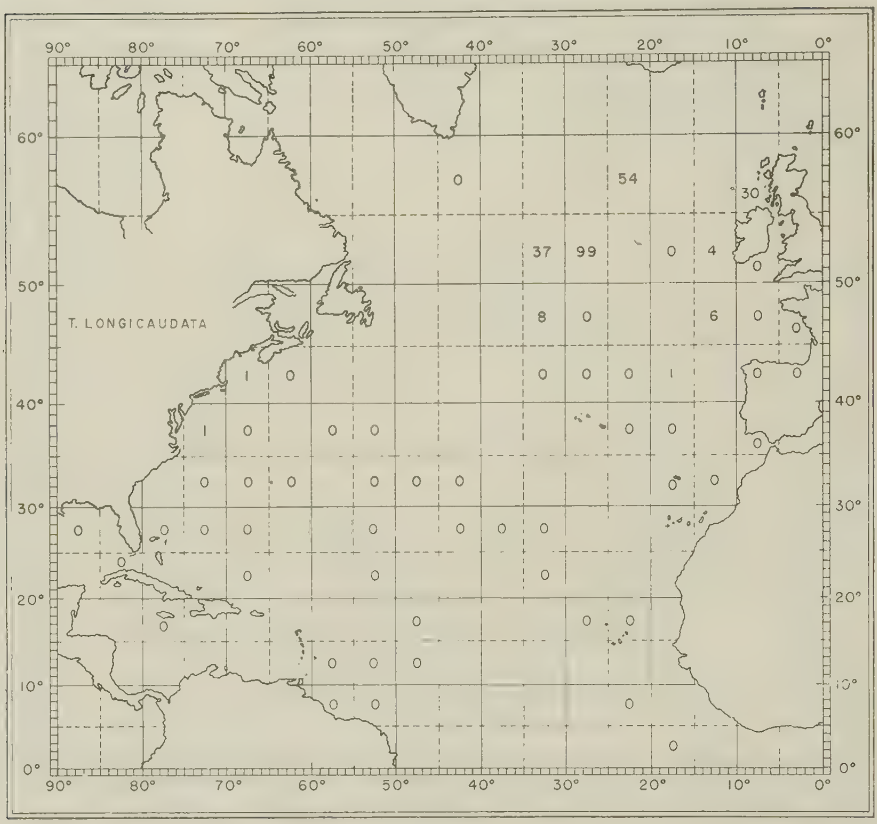
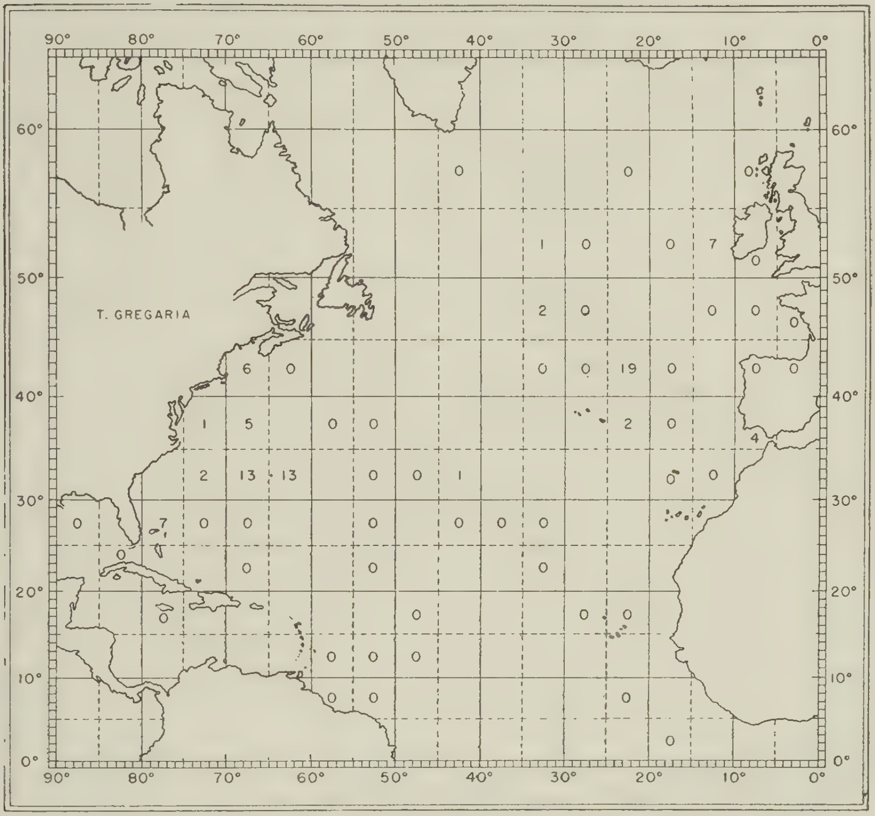


FIGURE 11.

TEMPERATURE DATA

The best night level temperatures to use would no doubt be the average or extreme value for the year at the depth occupied by each species at the locality in question. Lacking adequate information on the night levels occupied, we have had to make use of surface temperatures instead. Further, since maximum summer surface temperatures were used in previous work, this value has been retained here. While these cannot be taken as identical with the temperatures actually encountered by the animals, they may be assumed to be correlated with them but strictly they represent only certain surface characteristics of the water in which each species lives. Since hydrographic data were not always collected along with the net hauls, use has been


90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
60°
50°
40°
30°
20°
10°
0°
T. GREGARIA
0
0
0
1
0
0
7
0
2
0
0
0
0
6
0
0
0
19
0
0
0
1
5
0
0
2
0
4
2
13
13
0
0
1
0
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0
7
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0
0
0
0
0
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0
0
0
0
0
0
0
0
0

FIGURE 12.

made of charts of summer temperatures based on information in the hydrographic files of Woods Hole Oceanographic Institution. An error, due to the net hauls and the hydrographic observations not being simultaneous, is therefore introduced, but this is considered to be relatively unimportant.

Since, at the day level, both temperature and illumination are controlling factors, a combined factor was introduced in previous work. This was the illumination at the depth of 16°C. isotherm. In the present survey we are concerned primarily with temperature. In addition, areas are included where the temperature, even at the surface, is not as high as 16°. A more satisfactory factor to define deep conditions has therefore been found in the temperature at the depth at which the illumination at noon in summer has a value of 10^{-12} (re-

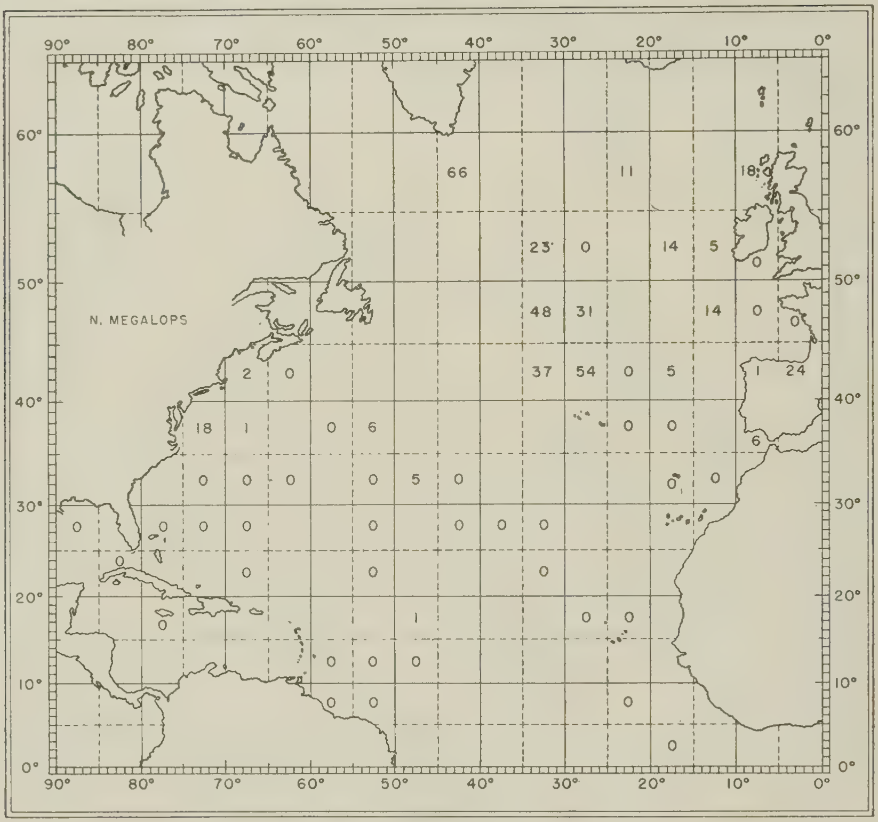

90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
60°
50°
40°
30°
20°
10°
0°
N. MEGALOPS
66
11
18
23
0
14
5
0
48
31
14
0
0
2
0
37
54
0
5
1
24
18
1
0
6
0
0
6
0
0
0
0
5
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
1
0
0
0
0
0
0
0
0
0

FIGURE 13.

ferred to hereafter as T_{I-12}). This is of more widespread application, but yields a very similar distribution pattern to $I_{T=16°}$ for the area of the western North Atlantic included in earlier work. As in the case of the night level temperature (T_S), this does not represent the actual day temperatures encountered by the Euphausids, but their variation from one area to another may be taken to be sufficiently closely correlated to allow certain comparisons to be made.

For the estimation of T_{I-12}, it is necessary to know the transparency of the water. Figures 15 and 16 show the distribution of extinction coefficients for the North Atlantic and Mediterranean areas. These are based on published information together with observations made by R. V. "Atlantis," U.S.C.G. Cutter "Evergreen" and other vessels, all of which are available in the hydrographic files already referred

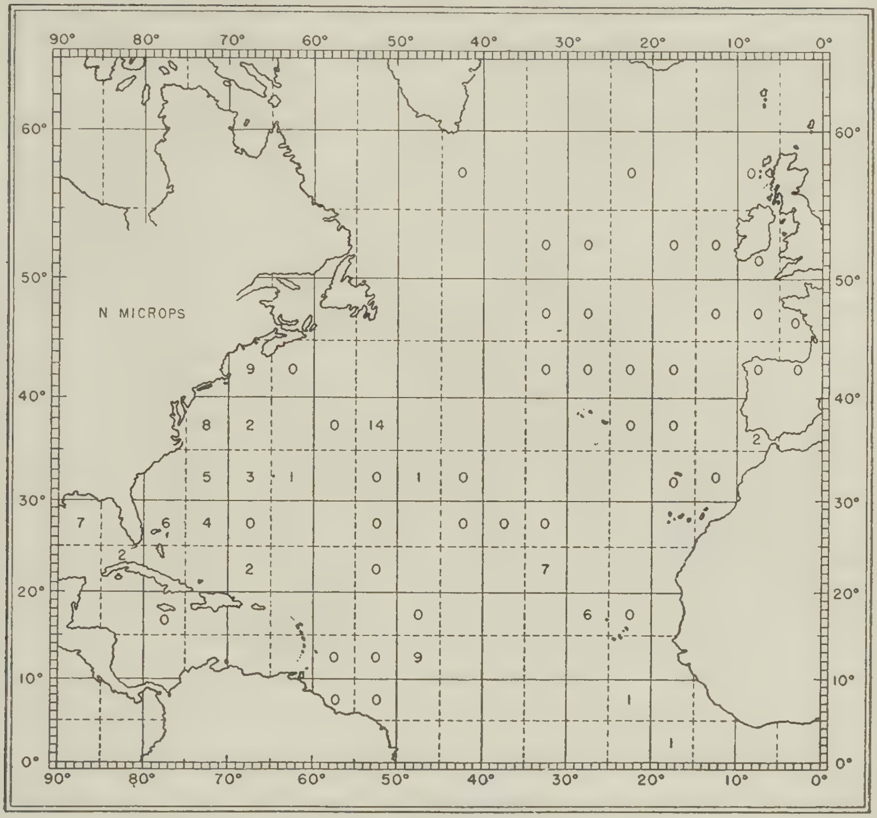
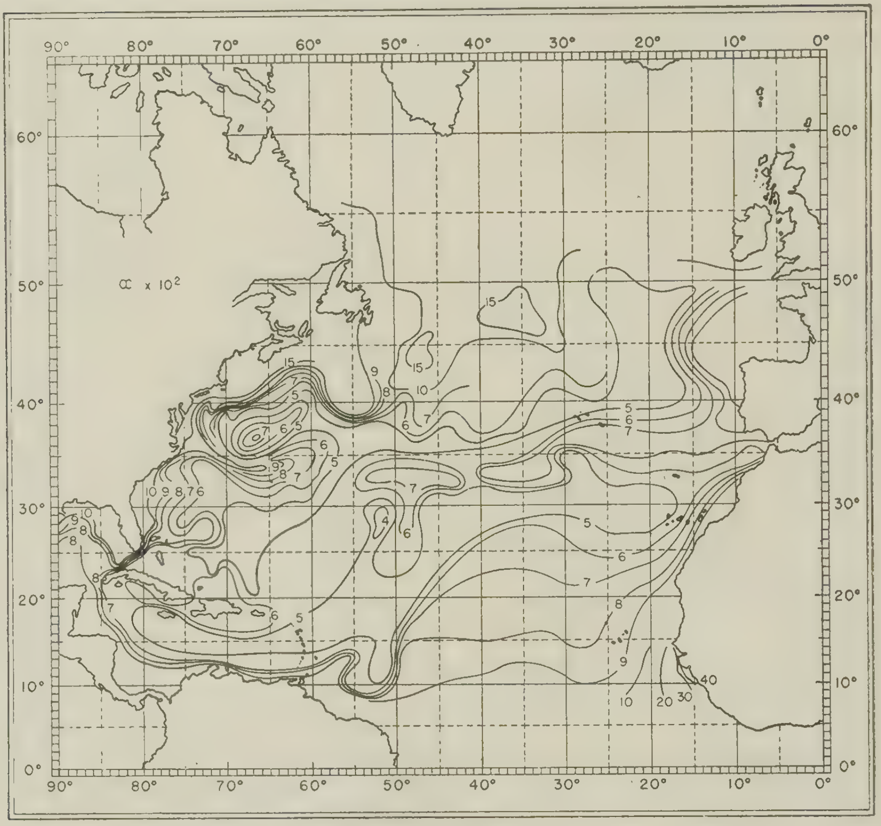

90° 80° 70° 60° 50° 40° 30° 20° 10° 0°
60°
0 0 0
0 0 0 0 0
50°
N MICROPS
0 0 0 0 0
9 0 0 0 0 0 0 0
40°
8 2 0 14 0 0 2
5 3 1 0 1 0 0 0
30°
7 6 4 0 0 0 0 0
2 2 0 7
20°
0 0 6 0
0 0 9
10°
0 0 1
1
0°
90° 80° 70° 60° 50° 40° 30° 20° 10° 0°

FIGURE 14.

to. These charts will require considerable revision when more observations are available. However, transparency like temperature, appears to be a characteristic of a water mass, and the close correspondence between the pattern in Figure 15 and that of temperature at a depth of 200 meters (Fuglister, *in litt.*) suggests that they are not grossly inaccurate. Charts of the depth distribution of 10^{-12} illumination at noon in mid-summer, were then prepared. This value, as in previous work, is based on a value of 100 arbitrary units at the surface with overhead sunlight. Finally, from available hydrographic data, charts of the distribution of T_{I-12} were prepared, as shown in Figures 17 and 18.



Figures 15, 16. Distribution of extinction coefficients. For simplicity, these are expressed as x 100.

Correlation between Specific Abundance and Temperature

For the whole North Atlantic and Mediterranean, there were 165 localities for which both Euphausid counts and the necessary temperature data were available. A graph was prepared for each Euphausid species in which the ordinates were T_S and $T_{I\text{-}12}$. Each locality was entered on the graph according to its temperature, and with a notation of the percentage of the species in question at that station. The resulting graphs are unsuitable for reproduction here, but they are summarized in Figure 19. With the variation from one locality to another in the adequacy of the net hauls, perfect consistency is not to be expected. The areas contoured indicate the limits of conditions beyond which the species is almost always absent, and the conditions

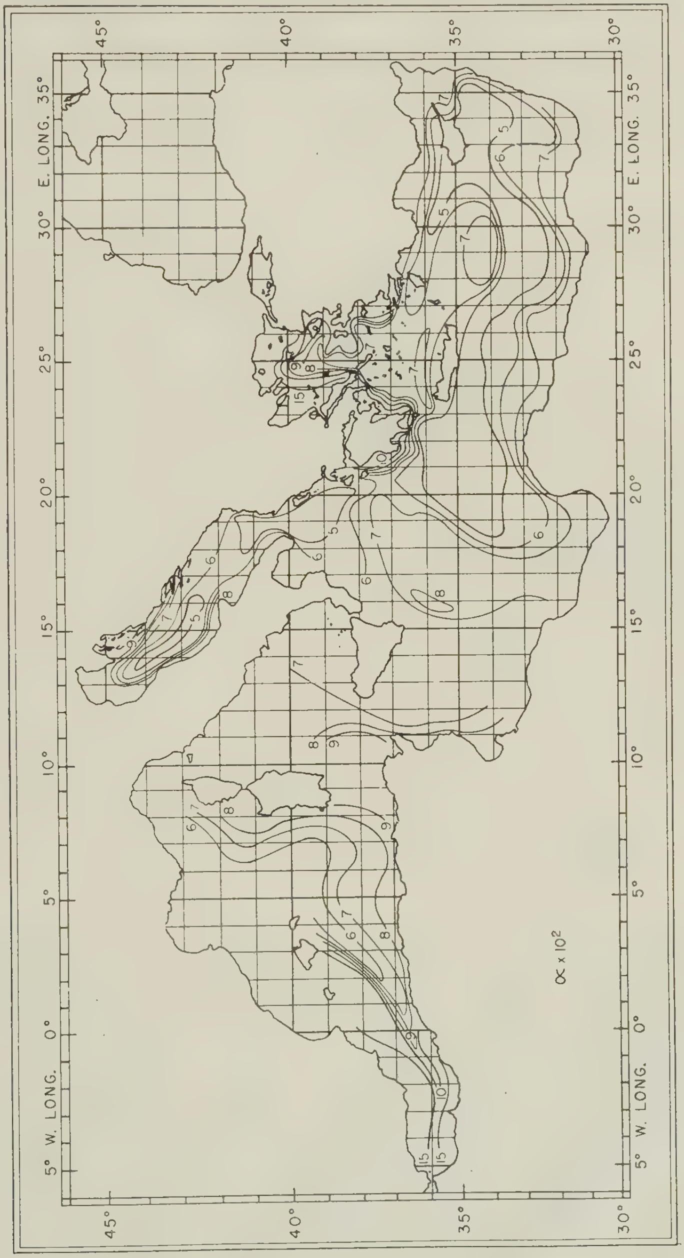
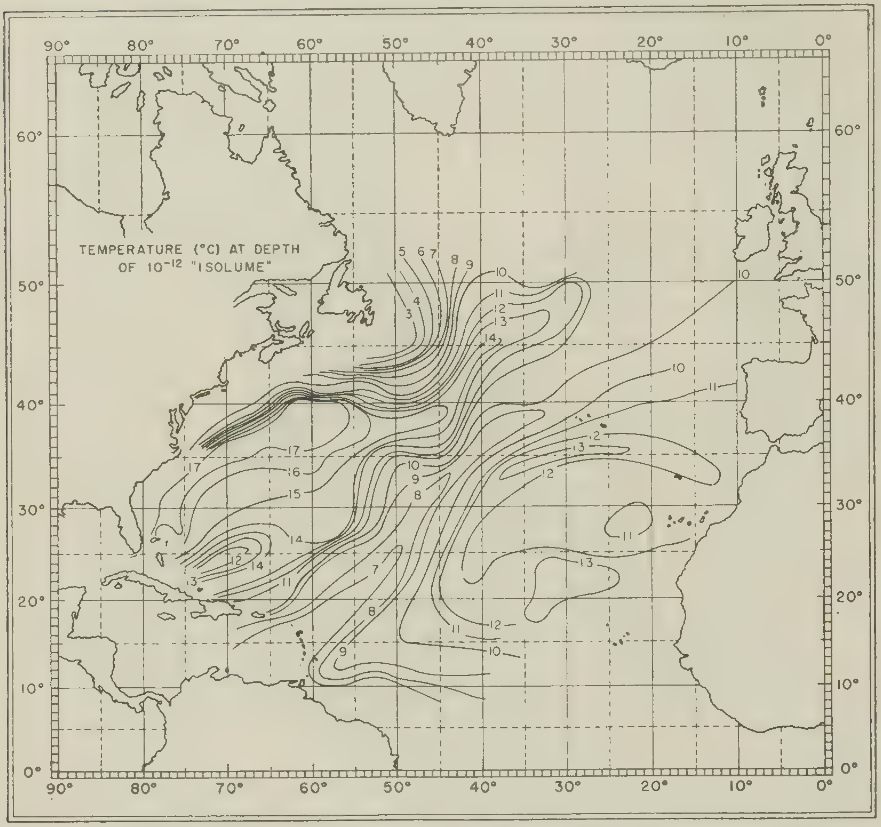

45°
40°
35°
30°
5° W. LONG.
0°
5°
10°
15°
20°
25°
30°
E. LONG. 35°
α x 10²

FIGURE 16.



FIGURES 17, 18. Distribution of temperature (°C.) at the depth of 10^{-12} illumination in summer.

under which it is most abundant. The data do not warrant more exact classification than this. However, both the general shape of the contoured areas, and their marked specific differences are significant. It should be noted that the lower right area of each graph represents improbable hydrographic conditions where $T_{I\text{-}12}$ approaches T_S in value, and from which observations are therefore lacking.

The absolute abundance of a given species is dependent, among other things, on the available food supply, and this varies considerably in different oceanic regions. The effect is eliminated by considering only the relative abundance of a species in the total Euphausid population. If, at a given locality, conditions were optimal for only one species, then that species would dominate in the population. If several

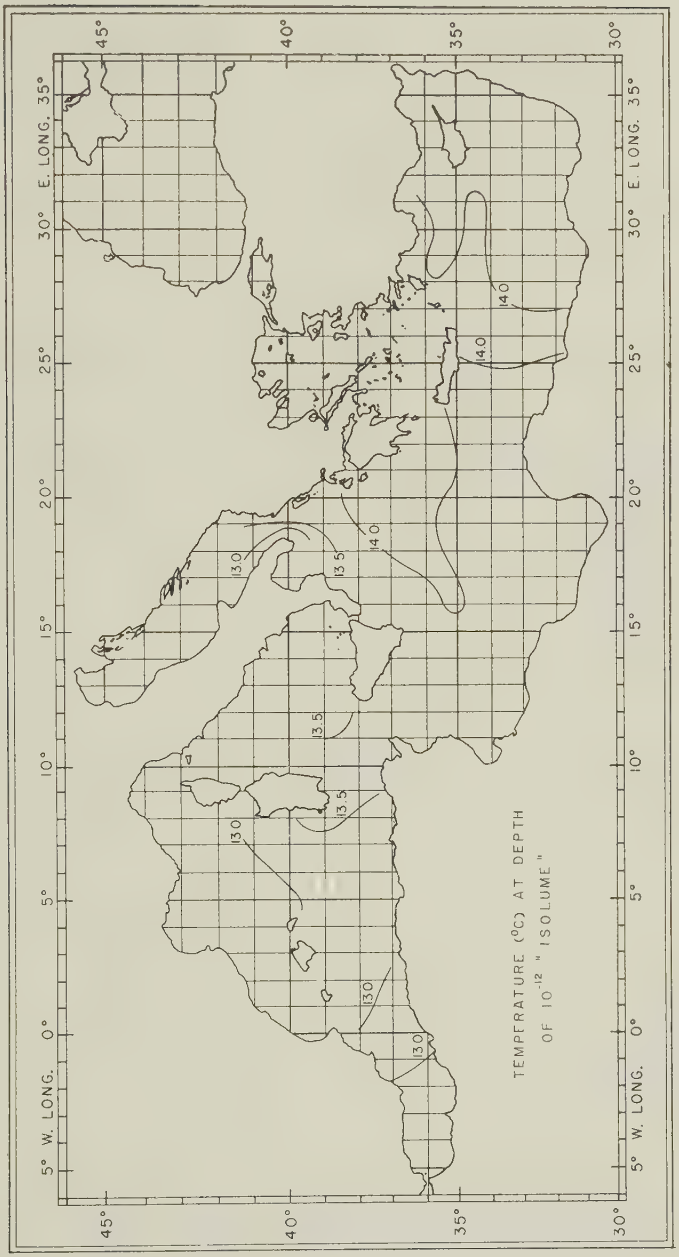

45°
40°
35°
30°
E. LONG. 35°
30°
25°
20°
15°
10°
5°
0°
5° W. LONG.
13.0
13.5
14.0
14.0
14.0
13.5
13.5
13.0
13.0
13.0
TEMPERATURE (°C) AT DEPTH
OF 10^{-12} "ISOLUME"

FIGURE 18.

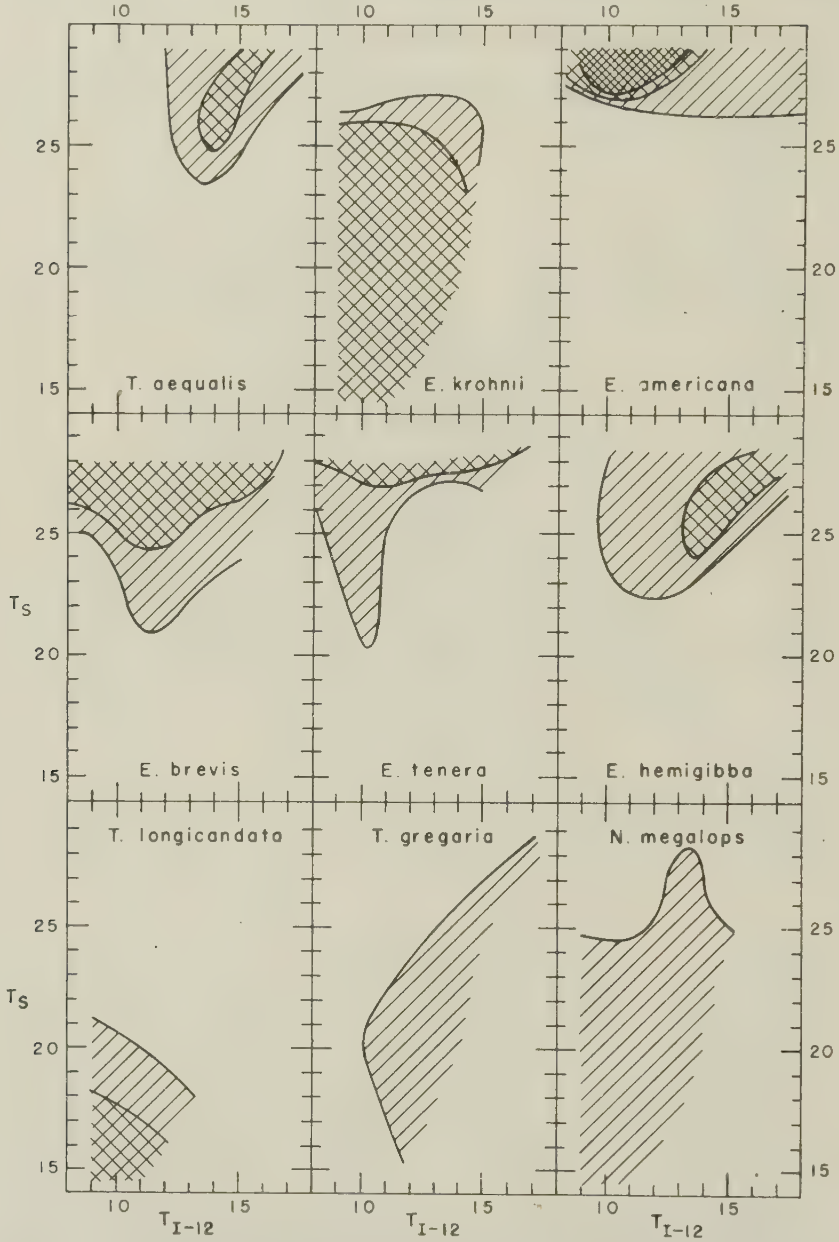


FIGURE 19. Relation between the abundance of the various species of Euphausids, surface temperature and temperature at the depth of 10^{-12} illumination. Relative abundance indicated by depth of shading.

species found optimal conditions in the same locality, then each would be represented by a smaller percentage of the total population. Thus the contours shown in Figure 19 may represent not simply the degree to which various temperature conditions suit each species, but also the amount of competition from other species under these conditions. In a crude attempt to eliminate this latter effect, a second series of contours was produced, based on data in which the observed percentage of the species at each locality was multiplied by the number of competing species present there. As only minor modifications of the contours resulted, it was felt that the uncorrected contours might be taken as a reasonable representation of the relation of the abundance of each species to temperature. As such, it is legitimate to compare them with the theoretical patterns presented in Figures 2-4.

The observed temperature relations of *Thysonoessa gregaria* (Figure 19) might be matched by a relationship similar to that shown in Figure 2. In this case, the optimum temperature would be about 21°C. or higher and the tolerance range about ±5°. Since the optimum appears to lie beyond the limit of our observations, it cannot be placed with any accuracy. It must be reiterated that the above statement does not imply that 21°C. is the optimum temperature for *T. gregaria*. The statement is that, under hydrographic conditions such that the summer maximum temperature at the surface, and also the temperature at the depth of 10^{-12} illumination in summer, both approach 21°, this species tends to be most abundant. Such conditions are unlikely to occur, and the abundance of this species reflects the departure of both T_S and T_{I-12} from this optimum. Furthermore, *T. gregaria* does not characteristically live either at the extreme surface at night or at the depth of 10^{-12} illumination in the daytime. In fact it appears to be a rather particularly deep living species, and one with a peculiarly variable day level.

Possibly *Thysanoessa longicaudata* shows a similar type of temperature relationship, but with a much lower optimum at about 11°C. This species was included solely to show a cold-water form for comparison, and its center of distribution lies in cold northern waters beyond those for which we have data, so no further attempt will be made to define its characteristics.

The remaining species, however, present a problem. They can all be matched, with greater or less exactness, by curves of the type shown in Figures 2-4. Thus *Euphausia brevis* and *E. tenera* approximate the pattern of Figure 3, in which there is a greater tolerance range for temperatures below than for those above the optimum. *Euphausia hemigibba* and *Thysanopoda aequalis* more closely resemble the contours in Figure 4, in which an allowance is made for a degree of physiological adaptation. In none of these species, though, does a single temperature optimum meet the requirements. If, on the other hand, it is assumed that the optimum value of T_S is higher than that of $T_{I\text{-}12}$ then good agreement is obtained.

It is true that the actual temperatures at the day and night levels of the species in question may not be as widely separated as the indicated values of T_S and $T_{I\text{-}12}$, but the implication still remains that there are different temperature optima at the day and night levels, and not a single optimum lying somewhere between the two. Furthermore, should it prove that temperature is not actually the operative factor, then the true factor would have to be one which is closely correlated with temperature, and as such showed two discrete optima. It is necessary, then, to justify the assumption of two temperature optima.

Allee, *et al.* (1949) state that "In the laboratory, organisms exposed to variable temperatures frequently, perhaps usually, show accelerated development as compared with those held at a constant temperature of the same value, if other conditions remain equal." They also point out that "the thermal optimum in the action of alternating temperatures may be different from the optimum for constant temperatures," and that "alternating temperatures may affect survival as well as the rate of development." Since different body processes differ in their optimum temperature, it might be expected that a fluctuating temperature, which allowed all the processes to enjoy optimum conditions for part of the time, might yield better results than any one fixed temperature which might be far removed from some of the optima. This is not a complete explanation, however, since work such as that of Parker (1930) has shown that exposure of grasshopper eggs to a temperature below that at which development takes place is followed by accelerated development when a higher temperature is resumed. It has been shown that spermatogenesis in many vertebrates has a lower optimum temperature than other body processes. There are more data available on limiting, than on optimum temperatures for such processes, but it appears that in such cases a fluctuating temperature is more favorable than a fixed one.

In the case of a diurnally migrating animal such as a Euphausid, it is safe to assume that at least some of the body processes differ in the day and night habitats. The food supply is more abundant in the night habitat. Increased feeding may, or may not imply more active swimming, but certainly involves more active masticatory and digestive processes. The evening ascent, involving extra energy expenditure, is into warmer water. Incidentally, if oxygen consumption increases with such increase in activity, the night levels favour this in having a higher oxygen concentration than the day levels. There is also a difference in water density of two to three thousandths between the two levels. While this is not great, the copepod *Calanus finmarchicus* has a density only about thirty thousandths greater than the sea water in which it occurs (Lowndes, 1942). If that is comparable with the density of a Euphausid, then the density of the latter, relative to the water, and hence its sinking rate, must be at least several per cent higher at the night level than at the day level. It appears, then, that at least energy expenditure is different in the two habitats. We are not in a position, at present, to assess the relative advantages of a varying and a stable environment, but the possibility that there is a definite advantage to the animal in thus alternating its environments, is not unreasonable. It is tempting to speculate further that the importance of diurnal migration lies in the attainment of such alternation of temperature.

Specific Temperature Relation Characteristics

From Figure 19 it is now possible to characterize the optimum hydrographic conditions for the dominance of the different Euphausid species. For *Thysanoesa longicaudata,* the optimum surface temperature lies below 14°C., which is the limit included in the area here surveyed. For *T. gregaria* the value would be about 21°C., and for *Nematoscelis megalops* and *Euphausia krohnii* perhaps the same, although the optimum is ill-defined. For *Euphausia hemigibba* and *Thysanoessa aequalis* the optimum is about 27°C., while for *E. americana, E. brevis* and *E. tenera* it is 28°C. or higher. $T_{I\text{-}12}$ optimum is below 8°C. for *Thysanoessa longicaudata,* and probably above 18°C. for *T. gregaria.* It is fairly clearly defined at above 10°C. for *E. americana,* 11°C. for *E. brevis,* 15°C. for *T. aequalis* and *E. hemigibba.* For *E. tenera* it is between about 10° and 15°C., and for *N. megalops* it is ill-defined, but possibly about 13°C. Finally, physiological adaptation appears to be more pronounced in *T. aequalis* and *E. hemigibba* than in the other species. *E. americana* is anomalous in that its tolerance range for $T_{I\text{-}12}$ appears to be greater above the optimum than below. If the data supporting this are adequate, then the effect may be

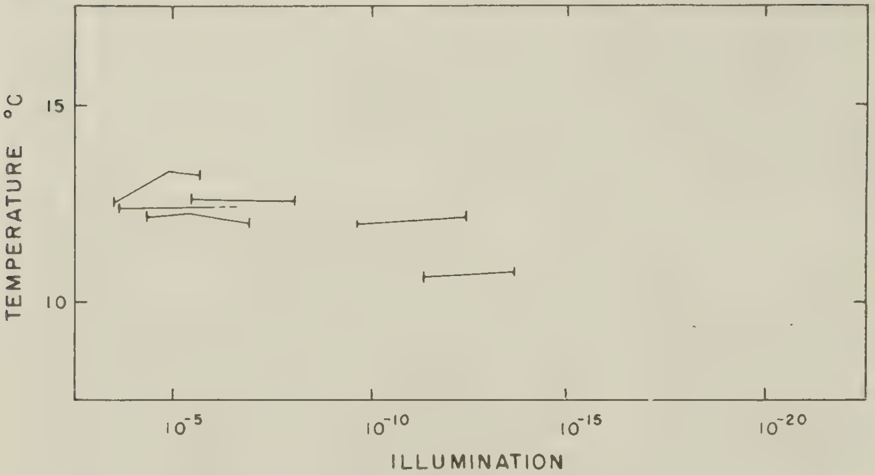


FIGURE 20. Data from a series of bathygrams showing the noon flattening period for what are believed to be pure populations of *Euphausia krohnii*. These show the conditions of temperature and illumination existing at the level of the scattering layer during the periods in question.

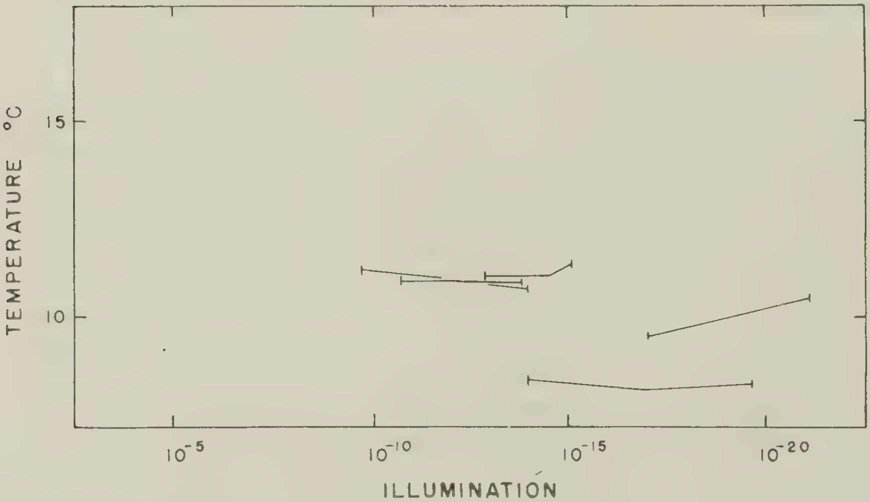


FIGURE 21. As in Figure 20, but for populations of *Nematoscelis megalops*.

genuine, but it may be that a factor other than temperature requires consideration here.

These values, as already emphasized, do not represent temperatures at the actual levels occupied by the Euphausids. If the Euphausid

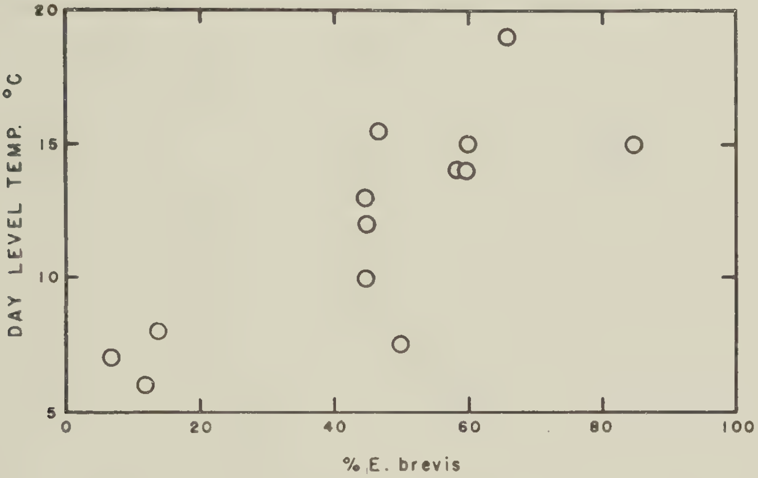


FIGURE 22. Correlation between the temperature at the level at which noon flattening occurs and the percentage of *Euphausia brevis* in the Euphuasid population.

origin of the phenomenon of the deep scattering layer be accepted, it is possible to obtain some information on critical temperatures at the actual depths concerned. A large proportion of the records of the daytime behaviour of this layer show periods of noon flattening which are interpreted as a change from illumination control to temperature control of depth. If the conditions of temperature and illumination under which this change-over occurs are compared with the composition of the local Euphausid population, it should be possible to define certain characteristics of the different species. In the presence of a large number of species, each with its differing reaction characteristics, such an analysis is impossible, and unfortunately this applies to the areas from which we have most records. In an area to the north of the Azores, and also in part of the Mediterranean, there is a very simple population composed almost solely of *Euphausia krohnii* and *Nematoscelis megalops*. Where this is found, their record appears as two separate layers on the bathygrams. Figures 20 and 21 show a series of such records with only the noon flattening period included, plotted in terms of temperature and illumination. It will be seen that for *E. krohnii* the critical temperature at which descent is arrested is about 12°C., and for *N. megalops* it is lower, but less well defined. The illumination at which flattening commences varies widely, but is about 10^{-5} to 10^{-15} for *E. krohnii* and 10^{-10} to 10^{-20} for the deeper-

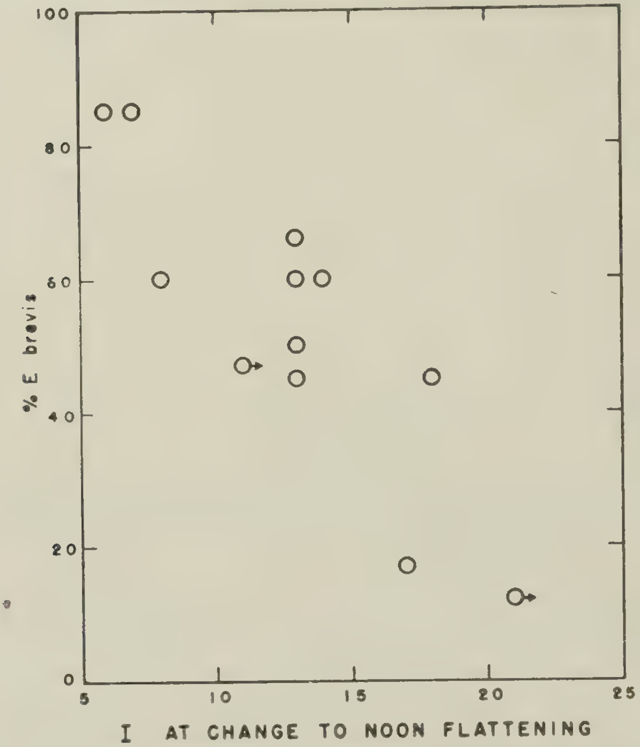


FIGURE 23. Correlation between the illumination at the level of the scattering layer at the time when descent ceases and noon flattening commences, and the percentage of *Euphausia brevis* in the Euphausid population.

living *N. megalops*. The apparently greater illumination tolerance range of the latter cannot be considered significant since illumination changes more rapidly around noon at these greater depths.

Analysis is also possible for *Euphausia brevis,* since this is an abundant species, and the other species with which it occurs are believed to be all deeper-living. Figure 22 shows the correlation between the temperature at the depth of noon flattening and the percentage of *E. brevis* in the population, and Figure 23 shows the similar correlation of the illumination at the commencement of noon flattening. In both cases, decrease in the proportion of *E. brevis* and corresponding increase in the proportion of other, deeper-living species results in noon flattening occurring at a lower temperature and illumination. By extrapolation to a 100 per cent *E. brevis* population, it would appear that this species descends at an illumination value of about 10^{-5}, and arrests descent at about 15-20°C. Figure 15 indicates optimum conditions for this species at about $T_{I-12} = 11\text{-}12°C$. In the part of the North Atlantic where such conditions coincide with the indicated value to T_S, 10^{-5} illumination occurs at noon at a depth of 150-200 fathoms, at which depth the temperature is 15-18°C. It appears, then, that this species tends to arrest its descent at about the depth at which it encounters its optimum day temperature. Further, since Euphausids have been shown to be able to migrate vertically more than fast enough to maintain themselves at a constant illumination, it may be assumed that the level of illumination at which they are observed to descend is that best suited to them. If this is the case, then the data indicate that *E. brevis* is most successful, as indicated by its relative abundance, in those localities where the illumination at the level of noon flattening is close to that indicated as optimum during their period of descent.

PREDICTION OF GEOGRAPHICAL DISTRIBUTION FROM THEORETICAL TEMPERATURE RELATIONSHIPS

A further check on the dual optimum temperature control theory may be obtained by comparing the observed geographic distribution of a species with that predicted from theoretical curves and known hydrographic conditions. The values of the two temperature optima selected, and the type of relationship between departure from these optima and survival index, are those which are found by trial to suit a particular species most closely. Beyond this, the theoretical and observed distribution charts are arrived at from independent data. If a rather complicated distribution pattern can be reasonably well duplicated by the two methods, there is a strong probability that the limiting factors and their mechanism of control have been correctly chosen.

As an example, it has been assumed that the temperature relationship for *Euphausia hemigibba* is of the type shown in Figure 4, with asymmetrical temperature response and a degree of physiological adaptation. Such a diagram was prepared, based on the temperature optima indicated for the species, and with a fuller series of survival index contours. From this, and charts of the distribution of T_S and T_{I-12}, the distribution of survival index for the species for the North Atlantic was calculated. Since maximum values for this were 100 per cent and *E. hemigibba* rarely comprises more than a third

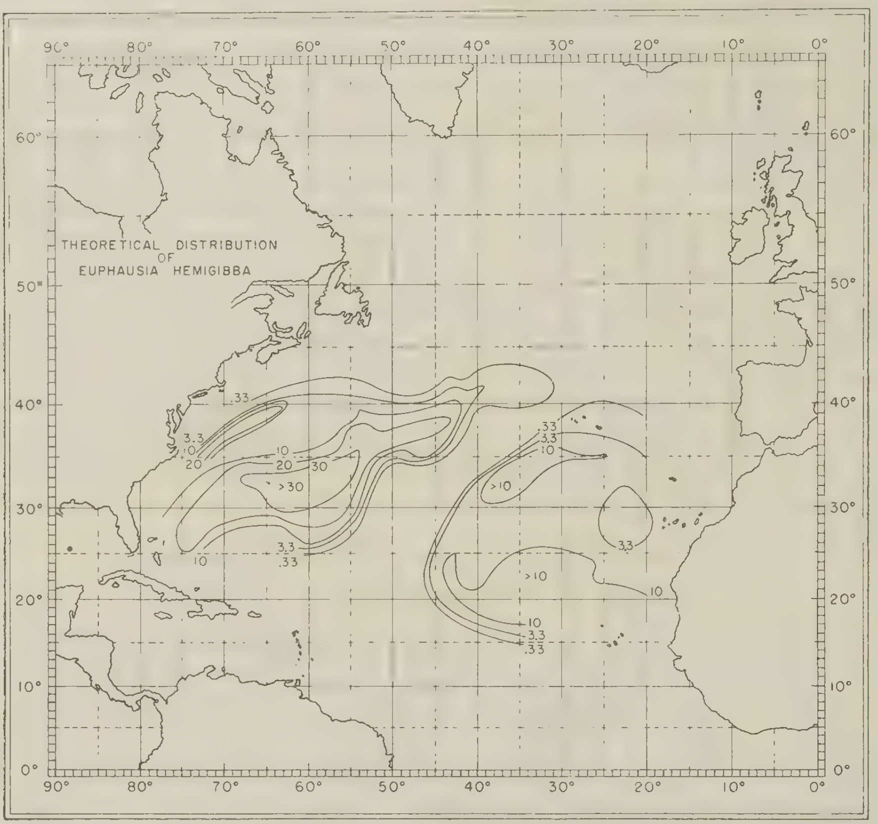

THEORETICAL DISTRIBUTION
OF
EUPHAUSIA HEMIGIBBA
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
60°
50°
40°
30°
20°
10°
0°
.33
3.3
10
20
10
20
30
>30
3.3
.33
10
.33
3.3
10
>10
3.3
>10
10
10
3.3
.33

FIGURE 24. Predicted distribution of *Euphasia hemigibba* for comparison with the observed distribution shown in Figure 10. For explanation, see text.

of the total Euphausid population, all values were divided by three to facilitate comparison with observed values. The results are shown in Figure 24, and should be compared with Figure 10. Considering the inadequacy of the net sampling in much of the area, and the oversimplified assumptions that have been made in the predicted distribution, the agreement between prediction and observation is good.

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Contribution No. 582

Transactions, American Geophysical Union Volume 33, Number 3 June 1952

BOTTOM PRESSURE FLUCTUATIONS DUE TO STANDING WAVES IN A DEEP, TWO-LAYER OCEAN

Henry A. Kierstead

(Contribution No. 582 from the Woods Hole Oceanographic Institution)

Abstract--The pressure fluctuation in a deep ocean, due to short-period surface waves, is calculated by means of a simple physical model. It is shown, as was pointed out earlier by Longuet-Higgins, that the pressure under a standing wave varies at twice the frequency of the wave and with an amplitude proportional to the square of the wave amplitude, and inversely proportional to the wave length, but that the pressure under a progressive wave is constant.

A similar calculation of the pressure fluctuation under a standing internal wave gives similar results, but the amplitude is diminished by the factor $(\Delta\rho/\rho)$.

Numerical calculations, using typical wave amplitudes, show that pressure fluctuations of about 30 cm may occasionally be expected under six-second surface waves, but that internal waves, because of their large wave lengths, will have little effect on the pressure in the deep ocean.

The purpose of this paper is to investigate the fluctuations of pressure at the ocean bottom due to surface and internal waves. LONGUET-HIGGINS [1950], by a rigorous analysis of the case of short-period waves, has shown that progressive waves cause no pressure fluctuations in deep water, but that in the presence of standing waves the bottom pressure varies with twice the frequency of the surface waves. We will not repeat his calculations, but will show how his results can be derived in a more elementary manner, and apply the same method to calculate the bottom pressure fluctuations due to short-period internal waves.

Under long-period waves the pressure can be calculated with sufficient accuracy from the height of water, on the basis of the usual hydrostatic assumptions, so this case requires no special consideration.

Free surface waves--We consider water of density ρ which is motionless except in the neighborhood of the surface. Let (x, y, z) be Cartesian coordinates with the origin on the mean surface and the z-axis directed vertically downward, and let P and V be the pressure and velocity vector. We will further assume that ρ is a constant at great depths. Then the equation of motion is

$$dV/dt = -\operatorname{grad}(P/\rho - gz) \qquad (1)$$

Therefore, there can be no pressure gradients, except for the hydrostatic term, in the deep water where V is zero. But P may vary with time providing it is the same at all points in deep water. We utilize this fact to calculate P by considering the motion of the column of water between the surface and the plane $z = z'$, and of such great lateral extent that the motion of water through its boundaries is negligible compared to the total mass. We denote by ζ the elevation of the free surface above the mean surface.

As has been pointed out by Longuet-Higgins, the center of gravity of this water column will rise and fall as a result of wave motion on the surface, except in the case of pure progressive waves. Vertical motions of the center of gravity can result only from the vertical components of external forces acting on the water mass. These forces are due to gravity, the external atmospheric pressure, and the pressure P at $z = z'$. Let z_0 be the depth of the center of gravity of the water column, M its mass, A its horizontal cross-sectional area, P' the dynamic pressure at $z = z'$, and P_0 the surface (atmospheric) pressure.

Then, by definition

$$P' = P - Mg/A - P_0 \qquad (2)$$

$$M = \int_A \int_{-\zeta}^{z'} \rho \, dz dS \qquad (3)$$

$$z_o = (1/M) \int_A \int_{-\zeta}^{z'} \rho \, z dz dS \tag{4}$$

By Newton's second law

$$M \, d^2 z_o/dt^2 = \int_A (P_o - P) \, dS + Mg \tag{5}$$

$$M \, d^2 z_o/dt^2 = A \, (P_o - P) + Mg = - AP' \tag{6}$$

if we assume the surface pressure to be constant and take z' great enough so that P is essentially independent of x and y. We will further assume for the moment that ρ is constant. Then

$$P' = - \, (M/A) \, d^2 z_o/dt^2 \tag{7}$$

$$P' = - \, (\rho/A) \, (d^2/dt^2) \, \left(\int_A \int_{-\zeta}^{z'} z dz dS \right) \tag{8}$$

$$P' = (\rho/2A) \, (d^2/dt^2) \, \left(\int_A [\zeta^2 - z'^2] \, dS \right) \tag{9}$$

$$P' = (\rho/2) \, (d^2/dt^2) \, \overline{\zeta^2} \tag{10}$$

where $\overline{\zeta^2} = (1/A) \int_A \zeta^2 \, dS$.

This is the result obtained by Longuet-Higgins in a more rigorous analysis of the wave motion.

Internal waves--We will now apply the same technique to a two-layer ocean. Taking the origin of coordinates at the free surface as before, let the density and average thickness of the upper layer be ρ' and h', and those of the lower layer be ρ and h. The height of the interface above the plane $z = +h$ will be denoted by ζ, and the elevation of the free surface above $z = 0$ by δ'. Equation (4) then becomes

$$z_o = (1/2M) \int_A \left[\rho \left\{ z'^2 - (h - \zeta)^2 \right\} + \rho' \left\{ (h - \zeta)^2 - \zeta'^2 \right\} \right] dS \tag{11}$$

$$P' = - \, (1/2A) \, (d^2/dt^2) \, \left(\int_A \left[\rho \left\{ z'^2 - \zeta^2 + 2h\zeta - h^2 \right\} + \rho' \left\{ \zeta^2 - \zeta'^2 - 2h\zeta + h^2 \right\} \right] dS \right. \tag{12}$$

$$P' = (1/2) \, (d^2/dt^2) \, \left(\rho \, \overline{\zeta^2} + \rho' \, [\overline{\zeta'^2} - \overline{\zeta^2}] \right) \tag{13}$$

$$P' = (1/2) \, (d^2/dt^2) \, \left(\rho' \, \overline{\zeta'^2} + \overline{\zeta^2} \, [\rho - \rho'] \right) \tag{14}$$

since $\overline{\zeta} = \overline{\zeta'} = 0$ by definition and $d^2h/dt^2 = d^2z'/dt^2 = 0$.

Pressure variations under harmonic waves--Equations (10) and (14) give the relation between the bottom pressure and the shape of the surface. However, this relation is more clearly seen if the surface motion is represented by harmonic waves. Because of Fourier's theorem, this results in no loss of generality.

We assume, then, that the surface displacement can be represented by the Fourier series

$$\zeta = \sum_{n=1}^{\infty} [A_n \sin (k_n x + \ell_n y + \omega_n t + \delta_n)] \tag{15}$$

where $\omega_n^2 = g \, (k_n^2 + \ell_n^2)^{1/2}$. Then

$$\zeta^2 = \sum_{n=1}^{\infty} A_n^2 \sin^2 (k_n x + \ell_n y + \omega_n t + \delta_n)$$

$$+ 2 \sum_{n=1}^{\infty\,'} \sum_{m=1}^{\infty} A_n A_m \sin (k_n x + \ell_n y + \omega_n t + \delta_n) \times \sin (k_m x + \ell_m y + \omega_m t + \delta_m) \quad . . . (16)$$

$$\zeta^2 = (1/2) \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} [A_n \sin (k_n x + \ell_n y + \omega_n t + \delta_n) + A_m \sin (k_m x + \ell_m y + \omega_m t + \delta_m)]^2 . \quad (17)$$

We see that ζ^2 is a sum of terms, each containing a pair of harmonic components. This means physically that the harmonic components interact in pairs, and characterizes the phenomenon as one of the second order. It will be necessary, therefore, to calculate the bottom pressure fluctuations due to the interaction of two harmonic components. The effect of any arbitrary surface motion can then be calculated by summing over all pairs of functions which occur in the Fourier expansion of ζ. Furthermore, the arbitrary phases δ_n may, without loss of generality, be made to vanish by a suitable choice of the origins of time and space. We therefore take

$$\zeta = A \sin (kx + \ell y + \omega t) + B \sin (k'x + \ell'y + \omega't) \quad . . . . (18)$$

where

$$\omega^2 = (k^2 + \ell^2)^{1/2} \quad . . . . (19)$$

$$\omega'^2 = (k'^2 + \ell'^2)^{1/2} \quad . . . . (20)$$

k, ℓ, k', ℓ', are arbitrary wave numbers, and A and B are arbitrary amplitudes. Then

$$\zeta^2 = A^2 \sin^2 (kx + \ell y + \omega t) + B^2 \sin^2 (k'x + \ell'y + \omega't)$$

$$+ 2 AB \sin (kx + \ell y + \omega t) \sin (k'x + \ell'y + \omega't) . \quad . . . . (21)$$

But

$$\sin^2 (kx + \ell y + \omega t) = [1 - \cos 2 (kx + \ell y + \omega t)]/2 . \quad . . . . (22)$$

The first term on the right is independent of t, while the second has an average value of zero.

Therefore, the third term in (21) is the only one which will contribute to $(d^2/dt^2)\,\overline{\zeta^2}$. We now use the trigonometric identity

$$2 AB \sin (kx + \ell y + \omega t) \sin (k'x + \ell'y + \omega't)$$

$$= AB \left[\cos \left\{(k - k') x + (\ell - \ell') y + (\omega - \omega')t\right\} - \cos \left\{(k + k') x + (\ell + \ell') y + (\omega + \omega')t\right\}\right] \quad (23)$$

But the right side of this equation has a mean of zero unless $k = k'$, $\ell = \ell'$, or $k = -k'$, $\ell = -\ell'$, either of which implies $\omega = \omega'$ because of (19) and (20). If $k = k'$, $\ell = \ell'$, (23) is replaced by

$$2 AB \sin^2 (kx + \ell y + \omega t) = AB [1 - \cos 2 (kx + \ell y + \omega t)] \quad . . . . (24)$$

with the constant mean AB. This is to be expected, since the center of gravity of a progressive wave moves horizontally, but not vertically.

We find, therefore, that a single progressive wave, or a linear combination of progressive waves with different wave lengths or directions of propagation, will not result in pressure fluctuations in the deep ocean.

On the other hand, if $k = -k'$, $\ell = -\ell'$, (23) becomes

$$2 AB \sin (kx + \ell y + \omega t) \sin (- kx - \ell y + \omega t) = AB [\cos 2 (kx + \ell y) - \cos 2\omega t] \quad . . . . (25)$$

Therefore

$$(d^2/dt^2)\,\overline{\zeta^2} = - AB (d^2/dt^2) \cos 2\omega t = 4 AB \omega^2 \cos 2\omega t \quad . . . . (26)$$

and from (10)

$$P' = 2\rho AB\omega^2 \cos 2\omega t = 2\rho g\, AB\, (k^2 + \ell^2)^{1/2} \cos 2\omega t \;\ldots\ldots\ldots\ldots (27)$$

We see that there are no pressure variations unless there exists in the surface waves a pair of harmonic components of equal frequency but opposite directions of propagation, which is the condition for standing waves. In this case the pressure will vary with twice the frequency of the surface waves. This is, of course, to be expected for a second-order effect and is supported by physical reasoning, since the center of gravity of a standing wave rises every half cycle and reaches its minimum elevation each time the surface passes through the mean surface.

If there are two layers of different density, the situation is more complicated, since there are two modes of vibration, in each of which both surfaces are in motion, but with different amplitudes. We consider first the high-frequency mode, analogous to free-surface waves, in which the two layers move together. For this mode the frequency is given by the usual relation

$$\omega'^2 = gk \;\ldots\ldots\ldots\ldots (28)$$

where k is the wave number in the direction of propagation. In view of our previous result that pressure variations arise only from the interaction of a pair of waves traveling in opposite directions, which holds for internal waves as well, we can, without loss of generality, assume the waves to be traveling along the x-axis. If we let

$$\zeta' = A' \sin (kx + \omega' t) + B' \sin (kx - \omega' t) \;\ldots\ldots\ldots\ldots (29)$$

then we have at the interface [LAMB, 1932]

$$\zeta = A' e^{-kh'} \sin (kx + \omega' t) + B' e^{-kh'} \sin (kx - \omega' t) \;\ldots\ldots\ldots\ldots (30)$$

Proceeding as before, but using (14) instead of (10), we readily find

$$P' = 2\omega'^2 A' B' [\rho' + \Delta\rho\, e^{-kh'}] \cos 2\omega' t \;\ldots\ldots\ldots\ldots (31)$$

$$P' = 2\, gk\, A' B' [\rho' + \Delta\rho\, e^{-kh'}] \cos 2\omega' t \;\ldots\ldots\ldots\ldots (32)$$

where

$$\Delta\rho = \rho - \rho' \;\ldots\ldots\ldots\ldots (33)$$

When the surface layer is deep compared to the wave length ($kh' >> 1$), we have

$$P' \cong 2\, gk\, A' B' \rho' \cos 2\omega' t \;\ldots\ldots\ldots\ldots (32a)$$

the same result as that obtained for a one-layer ocean, which is to be expected since in this case the lower layer is unaffected by the wave motion.

When kh' is small

$$P' \cong 2\, gk\, A' B' [\rho - \Delta\rho\, kh'] \cos 2\omega' t. \;\ldots\ldots\ldots\ldots (32b)$$

which shows the damping effect of a shallow surface layer.

For the other mode of vibration [LAMB, 1932, p. 372]

$$\omega^2 = gk\, \Delta\rho / (\rho \coth kh' + \rho') \;\ldots\ldots\ldots\ldots (34)$$

and

$$\zeta' / \zeta = -\Delta\rho\, e^{-kh'} / \rho' \;\ldots\ldots\ldots\ldots (35)$$

Let

$$\zeta = A \sin (kx + \omega t) + B \sin (kx - \omega t) \;\ldots\ldots\ldots\ldots (36)$$

and

$$\zeta' = -A\,(\Delta\rho/\rho)\,e^{-kh'}\sin(kx+\omega t) - B\,(\Delta\rho/\rho)\,e^{-kh'}\sin(kx-\omega t) \ldots\ldots (37)$$

Using (14) again, we find

$$P' = 2\,\Delta\rho\;AB\,\omega^2\,(1-e^{-kh'})\cos 2\omega t \ldots\ldots (38)$$

$$P' = 2\,gk\,AB\,(\Delta\rho)^2\,(1-e^{-kh'})(\sinh kh'\cos 2\omega t)/(\rho\cosh kh' + \rho'\sinh kh') \ldots\ldots (39)$$

$$P' = 2\,gk\,AB\,(\Delta\rho)^2\,(1-e^{-kh'}-e^{-2kh'}+e^{-3kh'})(\cos 2\omega t)/(\rho+\rho'+\Delta\rho\,e^{-2kh'}) \ldots\ldots (40)$$

When the surface layer is thin, the effect due to the free surface nearly cancels that due to the interface and (38) becomes

$$P' = 2\,g\,AB\,(\Delta\rho)^2\,k^3\,h'^2(\cos 2\omega t)/\rho \ldots\ldots (41)$$

On the other hand, when kh' is large, the motion of the surface is negligible and the pressure has its maximum value

$$P' = 2\,gk\,AB\,(\Delta\rho)^2(\cos 2\omega t)/(\rho+\rho') \ldots\ldots (42)$$

Comparing (40) with (32), we might expect the effect of internal waves to be small compared to that of surface waves when $\Delta\rho$ is small. But the amplitudes of internal waves are generally larger than those of surface waves by a factor of the order of magnitude of $\Delta\rho/\rho$. The ratio of the two effects will therefore depend on k, and since the wave lengths usually observed in internal waves are much greater than those observed in free-surface waves, the effect of free-surface waves will predominate in the bottom pressure fluctuations, as can be seen by reference to the numerical calculations below.

One further possibility must be discussed, that is, the interference between a free-surface mode and an interfacial mode of equal wave lengths but different frequencies ω and ω' given by (19) and (20) (with $\ell = 0$). We take

$$\zeta' = A'\sin(kx+\omega' t) - B\,(\Delta\rho/\rho')e^{-kh'}\sin(kx+\omega t) \ldots\ldots (43)$$

$$\zeta = A'\,e^{-kh'}\sin(kx+\omega' t) + B\sin(kx+\omega t) \ldots\ldots (44)$$

Neglecting terms that are independent of time, we have

$$\overline{\zeta'^2} = -(k\,AB\,\Delta\rho\,e^{-kh'}/2\pi\rho')\int_0^{2\pi/k}[\cos(\omega'-\omega)t - \cos\{2kx+(\omega+\omega')t\}]\,dx \ldots (45)$$

$$\overline{\zeta'^2} = -A'B\,(\Delta\rho/\rho)\,e^{-kh'}\cos(\omega'-\omega)t \ldots\ldots (46)$$

$$\overline{\zeta^2} = A'B\,e^{-kh'}\cos(\omega'-\omega)t \ldots\ldots (47)$$

$$\rho'\,\overline{\zeta'^2} + \Delta\rho\;\overline{\zeta^2} = 0 \ldots\ldots (48)$$

$$\therefore P' = 0 \ldots\ldots (49)$$

Therefore, interaction of the two modes of vibration cannot produce pressure changes in deep water.

Application to bottom pressure gages--In the design of bottom pressure gages and the interpretation of data obtained from them, it will be useful to have some crude estimates of the periods and amplitudes to be expected. The amplitudes (G) may conveniently be expressed in cm of water. Then

$$G = P'/(\rho g\cos 2\omega t) \ldots\ldots (50)$$

For the spectrum of surface waves we take a "typical" distribution of wave heights given by MUNK [1947]. This distribution has a maximum height (crest to trough) of four feet, at a period of eight seconds. Since we wish to estimate the effects of the largest waves which are commonly encountered, we have arbitrarily doubled the wave heights; that is, we have plotted Munk's wave heights as amplitudes. This spectrum is shown in curve 1 of Figure 1. We have used only that part of Munk's spectrum below a period of one minute, since longer waves do not satisfy the

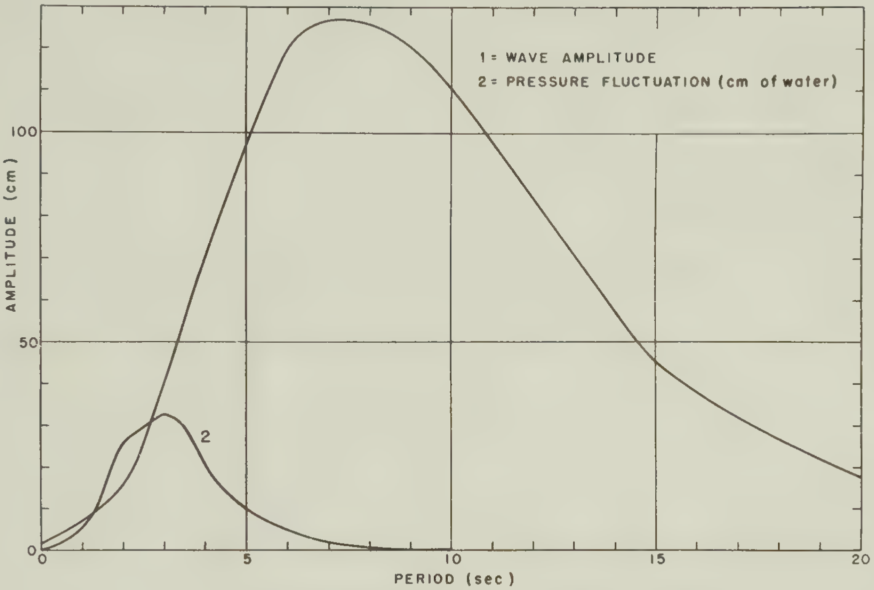

Fig. 1--Typical wave amplitudes and pressure fluctuations

condition for surface waves (L < 2h). From (27) (with $\ell = 0$) and (50) we find

$$G - 2\,AB\,k \qquad (51)$$

$$G = 2\,A^2rk \qquad (52)$$

where r = B/A is the standing-wave ratio. It is difficult to guess a typical value for r in the deep ocean. It is probably very small except near a moving storm or an island with a very steep shoreline. In any event, r can never exceed unity. We will assume in this calculation that r = 1, with the understanding that our results will represent upper limits to the effects that might be observed.

When the data of curve 1 are substituted for A in (52) with r = 1, we obtain the values of G plotted in curve 2. The greatest pressure fluctuation obtained is 32 cm of water at a period of three seconds. For this curve the periods are those of the bottom pressure, that is, half the wave periods.

Typical data on internal waves are more difficult to obtain, but it appears that oscillations of the seasonal thermocline at h′ = 200 m ($\Delta\rho/\rho \sim 3 \cdot 10^{-3}$) occur with periods of about 1000 sec and amplitudes in the neighborhood of 30 m, while the deep thermocline at about 1000 m ($\Delta\rho/\rho \sim 5 \times 10^{-4}$) oscillates at tidal periods with amplitudes not exceeding 100 m. The deep ocean pressure fluctuation due to waves on the seasonal thermocline is about 10^{-3} cm. The periods observed in the deep thermocline correspond to wave lengths in excess of 8×10^4 m, much greater than the depth of the ocean, so our method of calculation cannot be used in this case. A simple hydrostatic calculation shows that in this case the first-order pressure variation has an amplitude of about 1.2 cm in phase with the internal wave.

We can conclude, therefore, that a bottom pressure recorder with a sensitivity of, say, five cm of water, will record no effects due to internal waves, and that free-surface waves may possibly cause pressure fluctuations with periods of less than 30 sec, with a maximum amplitude not exceeding 32 cm of water at a period of three seconds.

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SEISMIC REFRACTION OBSERVATIONS NORTH OF THE BROWNSON DEEP*

By J. B. Hersey, Charles B. Officer, H. R. Johnson, and S. Bergstrom

ABSTRACT

Results of several refraction profiles made on the rise to the north of the Brownson Deep are presented. Good evidence for a high-speed layer with travel-time curves showing a compressional velocity of 7.94 km/sec. and an intercept of 8.4 sec. is presented, and the presence of an overlying lower-speed layer (6.64 km/sec., intercept 8.1 sec.) is demonstrated on less complete evidence. Neither layer correlates with existing reflection data in the area. Two sets of secondary low-frequency arrivals are tentatively interpreted as a refracted shear wave and a wave that has taken a bottom and surface reflection and then a basement refraction. Evidence is presented for a newly observed forerunner of the refracted-surface reflected waves of the permanent sound channel (RSR waves) consisting of a train of nearly constant frequency waves which appear to travel between surface and bottom via the RSR path and along the bottom at the speed of sound in water at the bottom.

I. Introduction

On March 15 and 16, 1949, the Woods Hole Oceanographic Institution's Research Vessels Atlantis and Caryn carried out a series of underwater sound-transmission experiments with the aid of a United States Navy destroyer, the O'Hare, DD889, to study the structure of the ocean floor north of the Brownson Deep by means of the seismic refraction method. The present paper describes the procedures used and discusses the results obtained. The techniques employed for receiving and recording the underwater sound were similar to those reported by Ewing *et al.*[1] Figure 1 is a chart showing the location of the receiving ships for the two profiles made on March 15 and 16. The general area is about 150 miles north of Puerto Rico and 60 miles north of the axis of the Brownson Deep.

II. General Description

In all the tests both Atlantis and Caryn were equipped with hydrophones which were lowered to depths of a few feet (not more than 150 feet) to receive sounds from 300-pound depth charges (TNT) dropped by the O'Hare. The two receiving ships were positioned about 50 miles apart and the O'Hare started dropping charges 20 to 30 miles on the far side of one, proceeding to roughly the same distance on the far side of the other. In one of the tests she reversed course and repeated the same

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[1] M. Ewing, J. L. Worzel, J. B. Hersey, F. Press, and G. R. Hamilton, "Seismic Refraction Measurements in the Atlantic Ocean Basin," *Bull. Seism. Soc. Am.*, 40: 233–242 (1950).

run, dropping her charges at different ranges from the first. These maneuvers should provide data for two end-to-end profiles and one reversed profile.

Topographically the area lies on the low rise that flanks the Brownson Deep on the north, the northern portion of the north-south profile extending over part of its northern slope. Water depths range from about 2,600 to 3,000 fathoms, being generally about 2,900 fathoms except near the western end of the east-west profile. (All depths are taken from echo-sounder measurements and are based on sound velocity of 4,800 ft/sec.) The ships were not equipped for bottom coring, and no data were obtained on the physical nature of the bottom sediments.

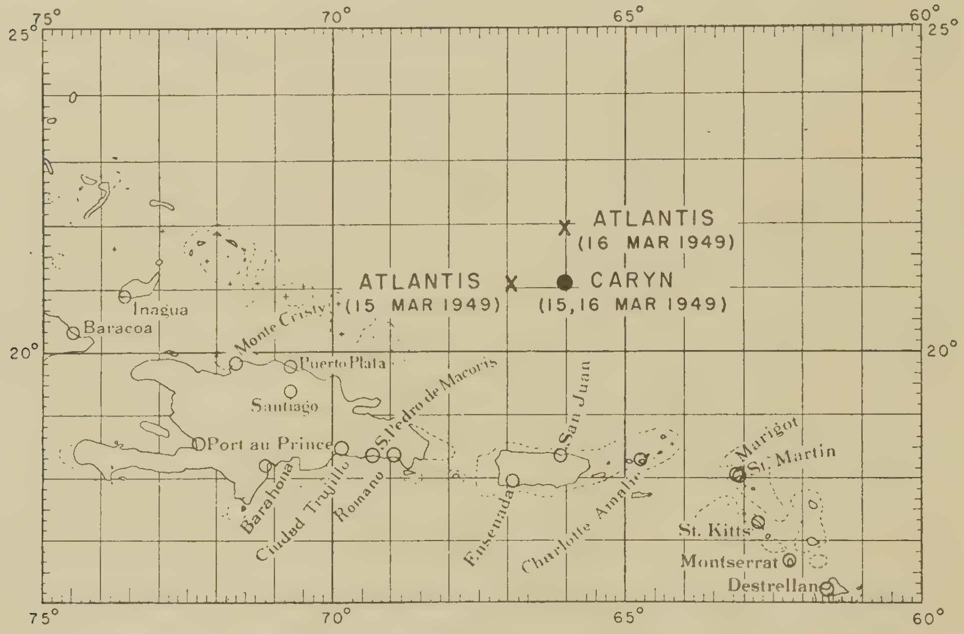
75°
70°
65°
60°
25°
25°
20°
20°
ATLANTIS
(16 MAR 1949)
ATLANTIS
(15 MAR 1949)
CARYN
(15,16 MAR 1949)
Inagua
Baracoa
Monte Cristy
Puerto Plata
Santiago
Port au Prince
Barahona
Ciudad Trujillo
Romano
S. Pedro de Macoris
San Juan
Ensenada
Charlotte Amalie
Marigot
St. Martin
St. Kitts
Montserrat
Destrellan
75°
70°
65°
60°

Fig. 1. Location of refraction profiles.

Hersey and Ewing[2] obtained a few vertical reflections in this area which were of M type. M-type records show a distinct second reflection recorded after the bottom reflection, having an amplitude about equal to it. This is regarded as coming from a reflecting horizon below the bottom since it is recorded only at rather low frequencies. Several additional records were made in the immediate vicinity of the refraction profiles and all were of M type. The technique employed to obtain these was essentially similar to that discussed by Hersey and Ewing[3] except that records were made while the ship was under way and the various frequencies recorded simultaneously rather than from successive shots. An example is shown in figure 2. The "filter frequency" is the center frequency of a band-pass filter broad enough to have a short time constant but steep-sided enough to discriminate strongly against energy in the adjoining frequency bands. The bottom reflection occurs 6.95 seconds after

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[2] J. B. Hersey and Maurice Ewing, "Seismic Reflections from beneath the Ocean Floor," *Trans. Am. Geophys. Union*, Vol. 30, No. 1 (1949).

[3] *Ibid.*

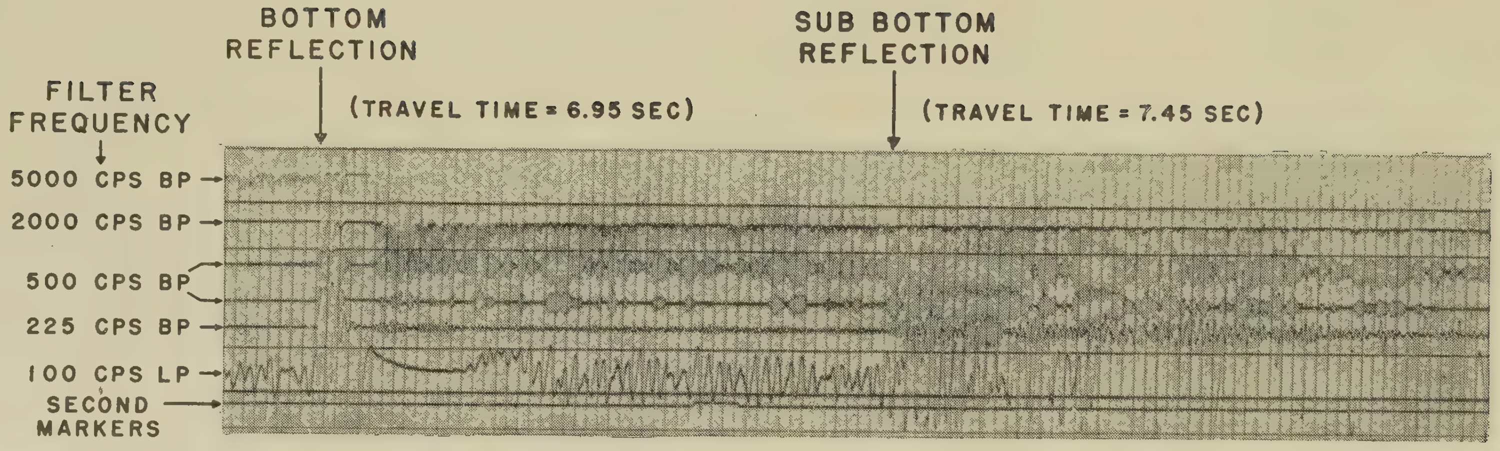

Fig. 2. A typical reflection record taken near the refraction profile.

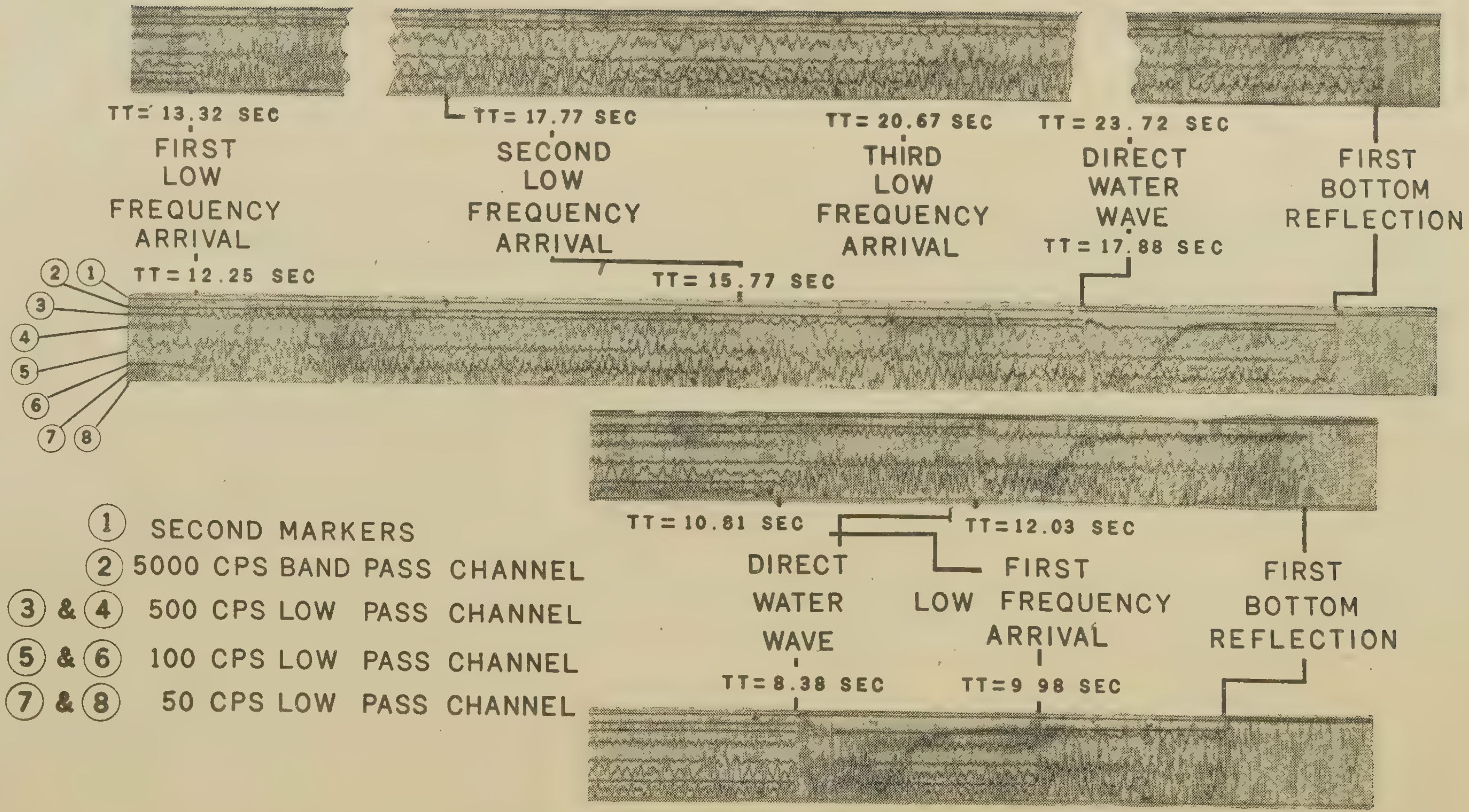

Fig. 3. Typical refraction records taken on R/V Caryn.

the shot instant (not shown) and is followed by a second more complicated arrival beginning at 7.45 seconds. This latter is recorded only on the traces having a 500-cps. filter or lower. At 8.4 seconds a third low amplitude arrival occurs only on the 100-cps. low pass trace. It is attractive to suppose this to be a reflection from a second horizon below the bottom. However, it cannot be positively identified as such since the other reflection records for this area are not of adequate quality either to deny or confirm its reproducibility. However, the first reflection after the bottom is reproducible and is observed even on the most inferior records. Table 1 gives the locations of reflection records taken in this vicinity and the bottom and first sub-bottom reflection travel times.

TABLE 1

Location		Bottom reflection	Sub-bottom reflection
Lat.	Long.	sec.	sec.
21° 03′ N	65° 13′ W	6.975	7.514
21° 03′ N	65° 15′ W	6.946	7.451
21° 03′ N	65° 21′ W	6.926	7.280
21° 04′ N	65° 30′ W	6.646	6.906
21° 04′ N	65° 35′ W	7.014	7.427
21° 05′ N	65° 45′ W	7.083	7.318

III. Experimental Procedure

The sound sources for all shots were depth charges (300 lbs. TNT) fired at a depth of 300 feet. The receiving ships were equipped with essentially identical receiving apparatus. The AX-58C hydrophone, a 45° X-cut Rochelle salt crystal unit, was the detector. It is fitted with a preamplifier of cathode follower type presenting a high input impedance to the crystal (about 50 megohms) to achieve good low-frequency response down to 5 cps. At higher frequencies its response is flat to about 20 kc. The hydrophone feeds a five-channel amplifier, each channel of which may be filtered in any required manner. Each channel is provided with two output stages at different dynamic levels for recording weak and strong signals on the same record. The amplifier outputs feed a bank of galvanometers, the deflections of which are recorded on photographic paper in a manner similar to the common practice in commercial seismic exploration. The recording camera on the Caryn had galvanometers whose response was flat to 400 cps., while those on Atlantis cut off at about 200 cps.

On the Caryn three channels of the five-channel amplifier were employed, with filters of 5,000 cps. (band pass), 500 cps. (low pass), and 50 cps. (low pass) each at two dynamic levels roughly 20 db. apart. A second single-channel amplifier fed by a second hydrophone employed a 100 cps. (low pass) filter. The line-up of traces is shown in figure 3. On the Atlantis two channels of the five-channel amplifier were employed, with 500 cps. (band pass) and 100 cps. (low pass) filters, both at two dynamic levels. A second amplifier and hydrophone of different design, which are sensitive only to frequencies above 100 cps., were also employed. The trace line-up is shown in figure 4.

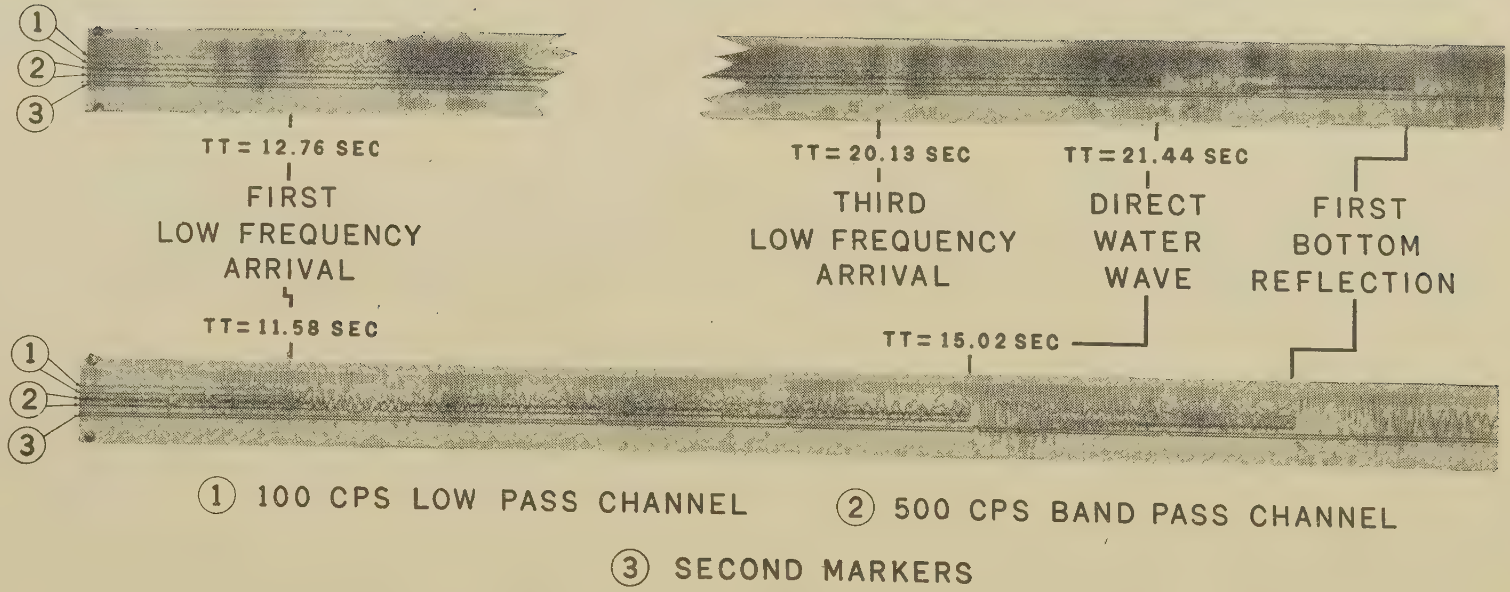

Fig. 4. Typical refraction records taken on R/V Atlantis.

All arrival times were referred to WWV by means of break-circuit chronometers, from which time was recorded on a timing trace on the photographic records. Similar records were made of the detonation of the depth charges aboard the O'HARE, from which the shot instants were computed relative to WWV. From these data travel times were computed and are believed to be accurate to about 0.13 second.

On March 15 the ATLANTIS and CARYN lay roughly 50 miles apart on an east-west line, as shown in figure 1. The O'HARE started at a point about 20 miles east of CARYN and dropped a charge every 10 miles to a point about 20 miles west of ATLANTIS. She then reversed course and dropped a charge every 15 miles back to her starting point. On March 16 the receiving ships again were about 50 miles apart on a north-south line (fig. 1). The O'HARE started her run 45 miles north of ATLANTIS and dropped charges every 8.3 miles. An irregular course resulted from a misunderstanding about the position of CARYN, which the O'HARE expected to be well to the westward. It was only after the run was nearly completed that the true situation was appreciated, too late to do much about it. Therefore, the CARYN did not receive an end-to-end profile.

The hydrophones were fitted with floats which would just buoy them up when only a short length of cable was in the water. At the shot instant the cable was paid out slowly so that the hydrophone sank slowly while receiving. The maximum depth was of the order of 150 feet. The last energy recorded arrived by various all-water paths and could readily be recognized by the observer. After these were observed the recording was stopped and the hydrophones recovered.

IV. WATER ARRIVALS

Sound-transmission records taken under conditions described in sections II and III, above, contain high-amplitude arrivals rich in high frequencies (figs. 3 and 4). These arrivals are energy which has followed paths solely in the water. The first arrival corresponds to paths between the source and receiver in the isothermal channel (fig. 5, path I). The next arrival corresponds to the first bottom reflection (fig. 5, path II.) In addition, second, third, etc., bottom reflection arrivals are obtained at correspondingly greater times. Owing to the vertical variation of sound velocity in water (see Fig. 5, path III), the first reflection will approach tangency to the bottom with increasing range. This corresponds to the RSR ray of Ewing and Worzel.[4] Beyond this range, energy arrivals are observed which are believed to correspond to a path in the isothermal channel and the RSR ray (see fig. 14). This is the path of least time for energy diffracted from the isothermal channel or scattered upon reflection from the sea's surface. The transmission of energy along this type of path has previously been demonstrated on several occasions in similar sound-transmission tests. There, travel time of the first bottom reflection plotted as a function of horizontal range correlated with a high-frequency arrival appearing at ranges greater than that corresponding to the RSR ray.

Figures 6, 7, 8, and 9 include plots of the travel time of the various water arrivals against the travel time of the direct water arrival for both ships on both days. It is to be noted that the reflection curves do not approach the 45° line through the origin,

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[4] M. Ewing and J. L. Worzel, "Long Range Sound Transmissions," Geol. Soc. Am., *Memoir 27* (1948).

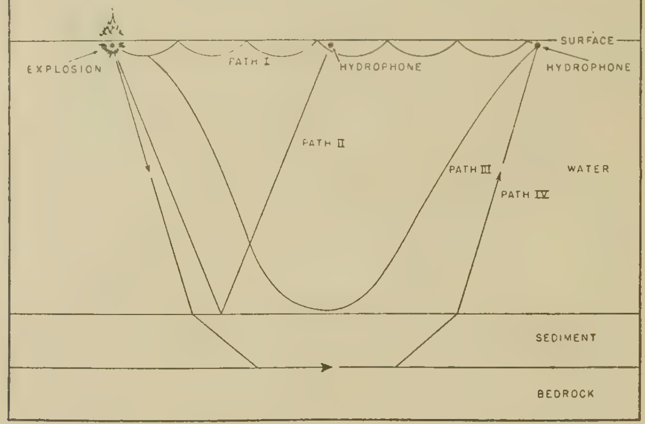
SURFACE
EXPLOSION
PATH I
HYDROPHONE
HYDROPHONE
PATH II
PATH III
PATH IV
WATER
SEDIMENT
BEDROCK

Fig. 5. Sound paths between explosion and hydrophone.

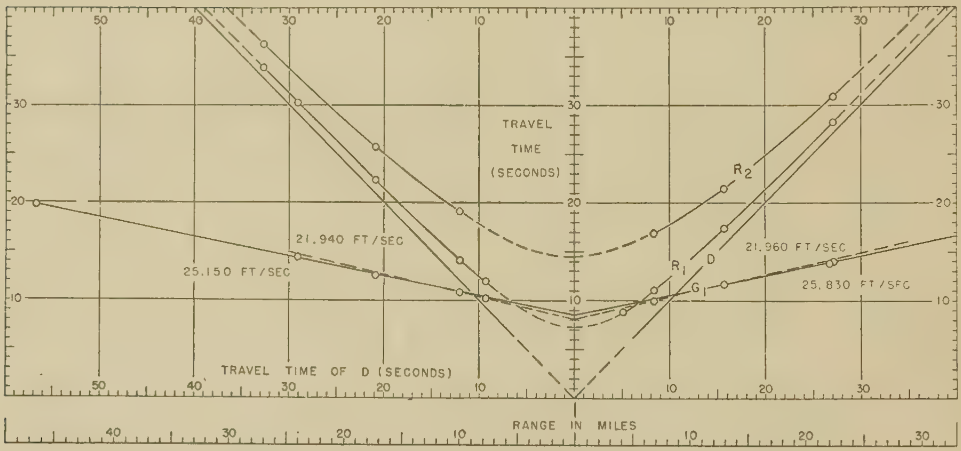

Fig. 6. Travel time vs. distance, March 15, 1949. Caryn receiving.

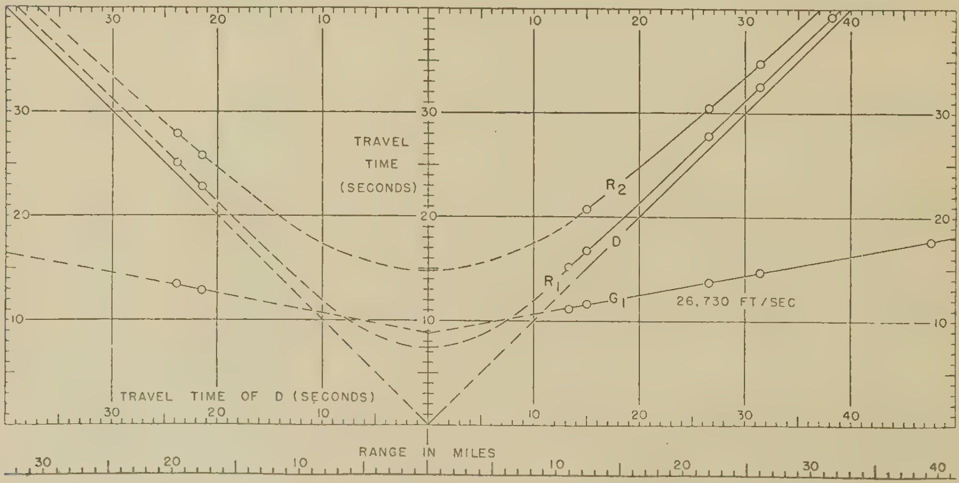

Fig. 7. Travel time vs. distance, March 15, 1949. Atlantis receiving.

but rather approach a 45° line with a vertical intercept of 1.0 and 2.0 sec. respectively. The time 1.0 sec. corresponds to the difference in travel time between the RSR path and the direct path, as determined by ray diagrams. The transition occurs at about 43 seconds, which corresponds to the travel time required for the RSR ray to reach the surface.

V. Ground Arrivals

On records taken at ranges greater than 6 miles a series of low-frequency wave trains were recorded before the arrival of the first bottom reflection. These are considerably more prolonged than the water waves and are of lower amplitude. Examples are shown in figures 3 and 4. The onset of the first wave train corresponds to the refraction arrival from the underlying high-speed medium (fig. 5, path IV). Plots of the travel time of the first low-frequency arrival against range (direct water-wave travel time) are given in figures 6–9.

TABLE 2

Ship	Day	Ground-wave velocity	Ground-wave velocity opposite end	Zero intercept
		ft/sec.	ft/sec.	sec.
ATLANTIS	15 March 1949	26,730	......	8.78
CARYN	15 March 1949	25,150	24,830	8.50
ATLANTIS	16 March 1949	26,520	25,440	8.54
CARYN	16 March 1949	25,830	......	8.78
	Average	26,060		
		= 7.94 km/sec.		8.65

The travel time along such a path is given by

$$t = \frac{C_0}{C_n} t_D + \sum_{p=1}^{n-1} \frac{2d_p\sqrt{C_n^2 - C_p^2}}{C_pC_n}$$

t = travel time of the refraction arrival
t_D = travel time of the direct water wave
C_0 = water sound velocity at the ocean surface
C_n = compressional velocity of the medium below the refraction horizon
d_p = thickness of the intermediate layers
C_p = compressional velocities of the intermediate layers.

Table 2 gives the values of velocity intercept for those profiles for which sufficient data were obtained for their measurement. The travel times plotted on these graphs have been corrected for shot depth, shot instant, and topography to a uniform depth of 2,900 fathoms. The generally good agreement between velocities obtained at the two receiving ships and between the two halves of the end-to-end profiles indicates that there was no radical sloping of the layer and that the average apparent velocity can be taken as the compressional velocity of the high-speed medium. The profiles reversed to within 0.2 second, at a range corresponding to the distance between the two ships as determined by navigation, showing the consistency in the data obtained by the two ships.

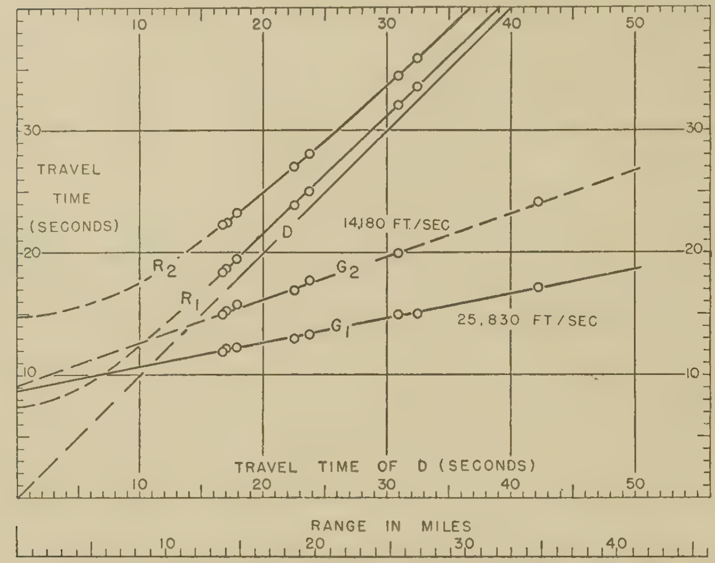

Fig. 8. Travel time vs. distance, March 16, 1949. Caryn receiving.

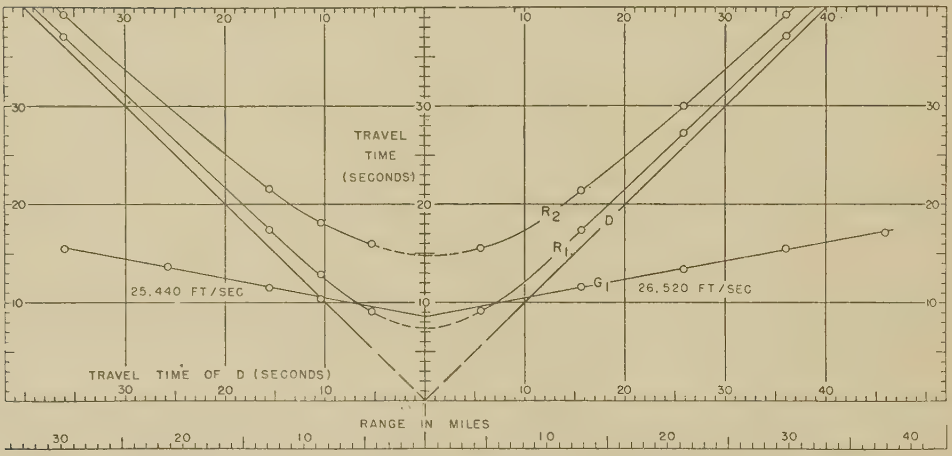

Fig. 9. Travel time vs. distance, March 16, 1949. Atlantis receiving.

The high-speed medium is well below the bottom since its intercept of about 8.6 seconds greatly exceeds 7.00 seconds as determined from the uniform depth of 2,900 fathoms for the bottom. Furthermore, it also exceeds the vertical travel time to the sub-bottom echo (about 7.6 sec.) discussed above. Since no reproducible sub-bottom echo was obtained here with as great a travel time as 8.6 seconds there is no evident correlation between this refraction horizon and the reflection data. The spacing of the shot points was such that very few records were obtained with values of t_D shorter than 16 seconds. These plot below the velocity line determined by more distant shots. From this it is suspected that a second high-speed layer, shallower than the first and of lower velocity, determined the first energy arrivals at the shorter ranges. In figure 10, which is a composite of all the data of the series of profiles, may be seen the evidence for this shallower layer. Here it is seen that all the arrivals on records with t_D less than 16 sec. lie on a line with slope corresponding to a velocity of 21,800 ft/sec. or 6.64 km/sec. and has an intercept of 8.10 sec. The case for this shallower layer would be considerably stronger if its presence were proved on a single profile, and such a test should be made as soon as possible. However, the evidence for it appears strong enough to warrant mention here.[5]

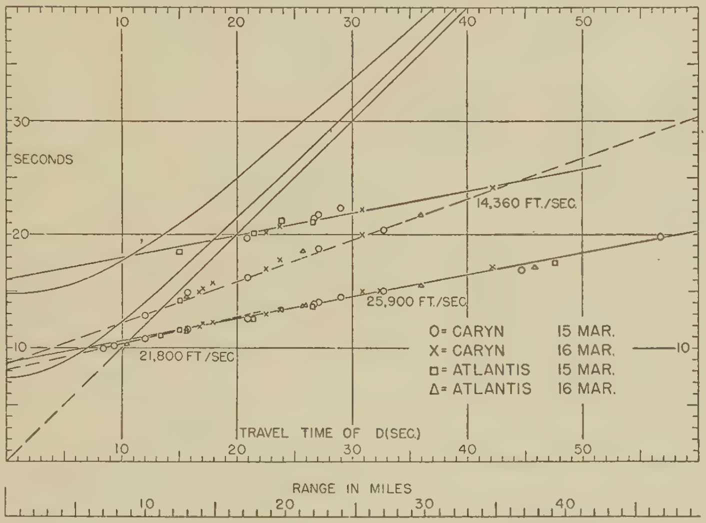

Fig. 10. Composite travel time vs. distance.

From recent earthquake and explosion seismological results on land[6] a range of velocities for P_n is from 7.78 km/sec. to 8.43 km/sec., whereas the range for the intermediate layer is from 6.41 km/sec. to 7.05 km/sec. Recent laboratory measurements of Hughes and Jones on small samples give 6.16 km/sec. for granite, 5.28 km/sec. for andesite, 5.95 km/sec. for quartz monzonite, 6.24 km/sec. for diorite, and 6.81 km/sec. for norite at a temperature of 30° C. and a pressure of 703 kg/cm.^{2} (pressure at the bottom of the ocean). It is noted that the velocities obtained from this set of profiles, 7.94 km/sec. and 6.64 km/sec., fall within the range of P_n and the second intermediate layer velocities respectively, and further, by comparison with the findings of Hughes and Jones,[7] that the lower velocity is associated with basic igneous rock rather than acidic rock.

Figure 11 is a summary of the information obtained from the first ground arrival. As no refraction results were obtained from the overlying sediments, it has been necessary to make an assumption about the character of the sediments. Two sets of calculations have been made. The first, following Ewing *et al.*,[8] has been made with a uniform sedimentary velocity of 5,600 ft/sec. The second set of calculations use a velocity of 5560 ft/sec. down to the "M" reflection horizon and a velocity of 14,140 ft/sec. for the underlying layer. These velocities are based on recent results reported by Officer *et al.*[9]

---

[5] A similar layering of the high speed basement has been found in the recent, more detailed results obtained by C. B. Officer, M. Ewing, and P. C. Wuenschel, "Seismic Refraction in the Atlantic Ocean Basin. Part IV: Bermuda, Bermuda Rise, and Nares Basin," *Bull. Geol. Soc. Am.*, 63:777–808 (1952), and by M. Ewing, G. H. Sutton, and C. B. Officer, "Seismic Refraction in the Atlantic Ocean Basin. Part VI: Typical Deep Profiles, North America Basin," not yet published.

[6] Ewing *et al.* (as cited in fn. 1, above), pp. 240–241.

[7] D. S. Hughes and H. J. Jones, "Variation of Elastic Moduli of Igneous Rocks with Pressure and Temperature," *Bull. Geol. Soc. Am.*, 61: 843–856 (1950).

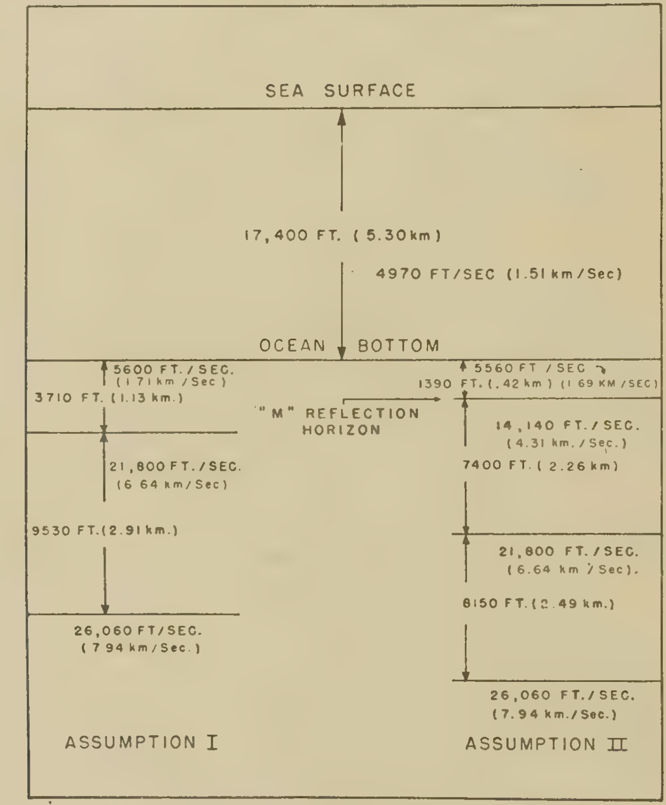
SEA SURFACE
17,400 FT. (5.30 km)
4970 FT/SEC (1.51 km/Sec)
OCEAN BOTTOM
5600 FT./SEC.
(1.71 km/Sec)
3710 FT. (1.13 km.)
21,800 FT./SEC.
(6.64 km/Sec)
9530 FT. (2.91 km.)
26,060 FT/SEC.
(7.94 km/Sec.)
ASSUMPTION I
5560 FT/SEC
1390 FT. (.42 km) (1.69 KM/SEC)
"M" REFLECTION HORIZON
14,140 FT./SEC.
(4.31 km./Sec.)
7400 FT. (2.26 km)
21,800 FT./SEC.
(6.64 km/Sec).
8150 FT. (2.49 km.)
26,060 FT./SEC.
(7.94 km./Sec.)
ASSUMPTION II

Fig. 11. Hypothetical seismic sections based on interpretation of ground waves.

In common with land seismic observations, the wave trains following the first arrival are complicated and vary in character in such a manner as to suggest significant energy arrivals of other types of waves. Many attempts to discover a consistent pattern of these characteristics from record to record failed. However, for the longer values of t_D on several records the first wave train died out completely and was followed by a period of one or more seconds long very nearly or quite as quiet as the ambient noise. This period is followed by the arrival of one or two wave trains rather similar in duration and amplitude to the first arrival. Where two later arrivals were picked, they were themselves separated by a period at least a second long of similar quiet. These arrivals are plotted on the composite graph (fig. 10) and may be seen in figures 3 and 4. On a few of the profiles sufficient data are available for determining that these arrivals form a consistent relationship. However, on many records the initial wave train is too long and complicated to permit our picking the start of any subsequent ones. Hence it is necessary to resort to a study of the composite travel-time graph of all the profiles. Here a consistent pattern appears.

---

[8] Ewing *et al.* (as cited in fn. 1, above).

[9] As cited in fn. 5, above.

The second arrival, interpreted as a velocity line, has an intercept of 8.7 sec. and a velocity of 14,200 ft/sec. (4.33 km/sec.). This line cannot be identified as a "masked" refraction of a shallow, lower velocity layer since its intercept is too large. The only other possibility that suggests itself is a shear refraction arrival from the underlying high-speed medium. The ratio of the compressional velocity (7.94 km/sec.) to the shear velocity (4.33 km/sec.) is 1.83 as compared with the theoretical value of 1.73, assuming Poisson's ratio.

No satisfactory interpretation was given to the set of third low-frequency arrivals from these data alone. However, recent refraction observations by Ewing *et al.*[10] have identified it as the refraction arrival from the high-velocity basement initiated by a wave that has taken one bottom and one surface reflection. This line has the same slope as the first arrival line and an intercept increased by approximately twice the bottom reflection time. It has been drawn in figure 10 and agrees crudely with the observed points.

A large-amplitude and singularly constant frequency arrival was observed on some of the records for both days. The waves always appear as a constant frequency forerunner to the RSR, last for about 1 second, occur only at ranges greater than 35 to 40 miles, and have a frequency of 63 cycles per second on records where precise measurements could be made. Figure 12 shows a set of records taken on the CARYN on March 16, 1949, illustrating the character of this arrival. A graph (fig. 13) of the time difference between this arrival and the refracted water wave arrival $(t_A - t_B)$ versus the travel time of the RSR arrival (t_A) gives a straight line with a slope of about 0.01 and a horizontal intercept of 43 seconds. The first two points of this graph do not appear as a single frequency forerunner, but as a complicated high-amplitude arrival which precedes the expected time of the RSR arrival. It is noted that this intercept corresponds to grazing incidence for the first reflection, i.e., the RSR arrival. A possible explanation for this phenomenon is obtained if it is assumed that the forerunner starts out along the RSR path, travels along the bottom, and comes back to the surface along the RSR path (fig. 14). The horizontal distance between source and receiver is given by the following expressions:

$$d = C_1 t_1 + D, \quad \text{and} \quad d = C_3 t_3 + D$$

where t_3 is the travel time for the refraction path and D is the horizontal distance of a single RSR cycle.

Then, as $t_B = t_3 + t_2$, $t_A = t_2 + t_1$, and $C_1 t_1 = C_3 t_3$

$$(t_A - t_B) = \frac{C_3 - C_1}{C_3} t_A + \frac{C_1 - C_3}{C_3} t_2$$

---

[10] As cited in fn. 5, above.

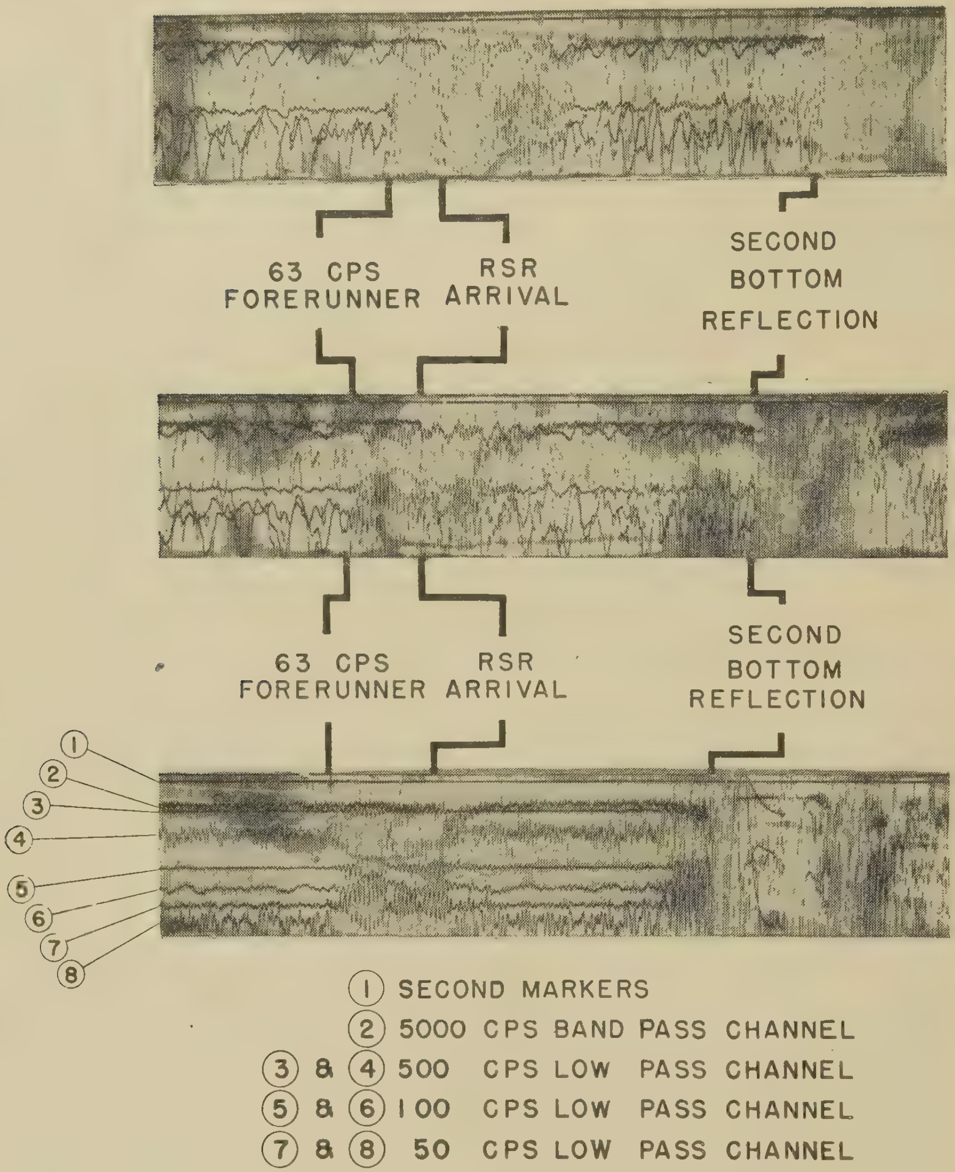

Fig. 12. Seismic records showing constant frequency forerunner of the RSR arrival.

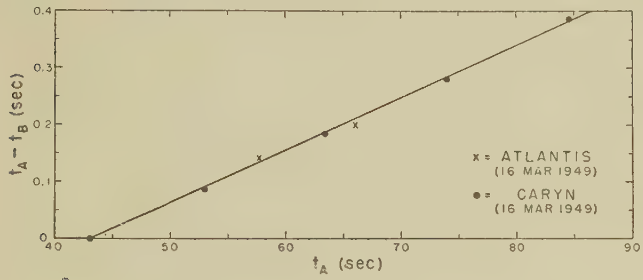

Fig. 13. $t_A - t_B$ vs. t_A.

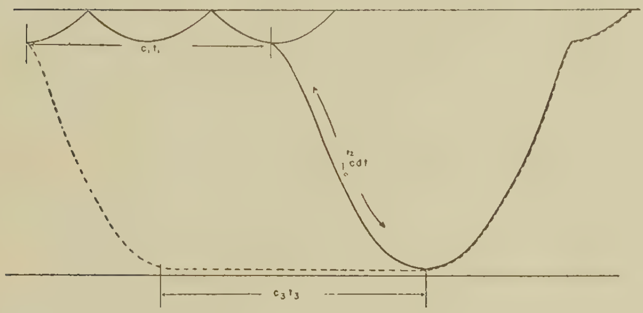

Fig. 14. Sound paths for RSR arrival and its forerunner.

For the horizontal intercept

$$t_A = t_2 = 43 \text{ sec.}$$

which agrees with the refraction travel time obtained from the reflection-refraction profile.

For the slope,

$$\frac{C_3 - C_1}{C_3} = 0.01$$

$$C_3 \sim 1.01\, C_1$$

which agrees with the value of the velocity of sound at the bottom of the ocean obtained from hydrographic data.

While the observed travel times correspond to the analysis presented here, no mechanism has suggested itself to account either for this type of transmission or for its remarkably single-frequency characteristic. Recent theoretical and experimental work by Press *et al.*[11] on air-ice-coupled flexural waves may lend itself to an explanation of this phenomenon.

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[11] F. Press, A. P. Crary, J. Oliver, and S. Katz, "Air-Coupled Flexural Waves in Floating Ice," *Trans. Am. Geophys. Union*, 32: 166–172 (1951), and F. Press and M. Ewing, "Theory of Air-Coupled Flexural Waves," *Jour. Appl. Physics*, 22: 892–899 (1951).

VI. SUMMARY

1. First low-frequency arrivals, interpreted as refracted waves, show the presence of a high-speed layer having a velocity of about 26,060 ft/sec. or 7.94 km/sec. whose intercept of 8.6 sec. is too great to identify the layer with M-type reflection records now available in the area.

2. A lower-speed layer having a velocity of about 21,800 ft/sec. or 6.64 km/sec. and an intercept of 8.1 sec. is indicated by the collected evidence from short range shots from the four profiles, though its presence could not be satisfactorily demonstrated on any one profile because of the paucity of short-range data.

3. The two compressional velocities determined by the first arrivals compare with P_n and the velocity of the intermediate layer respectively determined on land by various methods, and the lower of the two velocities compares with basic igneous rock velocities at laboratory pressures corresponding to oceanic depths.

4. Two later arrivals are identified tentatively as a refracted shear wave of the high-speed layer and a compressional refracted wave which has initially taken one bottom and one surface reflection.

5. Evidence for a newly observed low-frequency arrival is presented which appears as a nearly single-frequency wave train observed as a forerunner of the RSR arrival. The interpretation is offered that this energy traveled to and from the bottom by the RSR path and along the bottom at the water velocity there. The suggestion is offered that this wave train may have an explanation similar to the single-frequency air-coupled flexural waves observed in ice by Press *et al.*[12]

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[12] As cited in fn. 11, above.

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FISH AND WILDLIFE SERVICE, Albert M. Day, *Director*

FACTORS INFLUENCING THE ORIENTATION OF MIGRATING ANADROMOUS FISHES

By Gerald B. Collins

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FACTORS INFLUENCING THE ORIENTATION OF MIGRATING ANADROMOUS FISHES

By Gerald B. Collins, *Fishery Research Biologist*

HISTORICAL BACKGROUND

The orientation of migrating fishes has been the subject of investigation and conjecture for many years. Migration paths have been outlined by tagging experiments, and a wealth of valuable information on the physiology, development, and behavior of migratory fishes has been acquired through the persistent efforts of many able investigators; but the means by which the fish are directed on their migrations are still largely a matter of speculation.

The purpose of the study presented here was to investigate the influence of certain physical and chemical factors upon the orientation of migrating anadromous fish of the genus *Pomolobus*. In the course of this investigation an effort was made to determine experimentally if the migrating fish would orient to differences in the physical and chemical characteristics of water.

The existence of differences in physical and chemical factors in natural waters to which fish might respond has long been known. Slight gradations usually exist in the relative amounts of dissolved gases, in pH, in temperature, and in other physical and chemical characteristics of a stream from the source to the mouth. Such gradients are usually so slight that the differences between points miles apart are still below the thresholds of the sensory perception of fish.

Much greater gradients are found at stream junctions and at stream entrances into lakes or into the sea. In these gradients there frequently are chemical and physical differences between points a few feet apart which are large enough to be detected by the fish. The existence of these gradients at crucial points along the migration paths of anadromous fishes where they might influence the fish in the selection of a stream has led to speculation on their possible role in directing the migration of the fish.

The author is greatly indebted to Prof. George L. Clarke of Harvard University for his encouragement, helpful suggestions, and criticisms during this research. The work was done in partial fulfillment of the requirements for the degree of doctor of philosophy at Harvard University, Department of Biology.

Thanks are due also to Prof. Alfred C. Redfield and many other members of Harvard University and the Woods Hole Oceanographic Institution for their advice and aid in securing funds and special equipment. The research during the summer of 1949 was done while occupying a research fellowship at the Woods Hole Oceanographic Institution.

The cooperation of the town of Bourne, Mass., is acknowledged for permission to work in Herring River and to use town property at Bournedale.

A special debt is gratefully acknowledged to Director Francis W. Sargent and John Burns of the Division of Marine Fisheries, Massachusetts Conservation Department, for their interest and aid which made this investigation possible. The research in the spring of 1949 was done as an employee of the Massachusetts Division of Marine Fisheries.

The encouragement and aid of Dr. Lionel A. Walford, Ralph P. Silliman, Clinton E. Atkinson, and others of the Fish and Wildlife Service are also acknowledged. The research in the spring of 1950 was done as an employee of the U. S. Fish and Wildlife Service.

MAJOR THEORIES ON ORIENTATION

Currently, two major concepts on the orientation of migrating anadromous fishes have gained wide support; and, while not mutually exclusive, they are, as the frequent clashes in the literature suggest, not entirely compatible.

One of these theories regards the upstream migration of the fish as a purposeful "homing" to the part of the river system in which it was hatched or in which it spent the early stages of its life. Memory impressions of the goal or home are implied and the fish is said to be seeking its spawning area. The fish is thought to return to its native stream because that was the place where it was spawned rather than because the stream was more accessible or made more attractive by immediate environmental conditions. The fact that significant numbers of fish have actually been observed to return to the streams from which they originated is frequently used as evidence for this homing viewpoint.

The other theory is that environmental factors control the direction of migration, and therefore physical and chemical conditions such as temperature, current, amounts of dissolved gases, or odors, are thought to determine the ultimate destination of the fish. These factors fluctuate and are duplicated in nature so that migratory fish could go to any stream with these conditions.

Those who support the idea of environmental control of the direction of migration present evidence that the fish responds to its immediate environment at each point of its migration and they look upon the migration itself as merely the sum of the successive responses. The various species are thought to arrive at their separate destinations because they respond in specifically different ways to the existing patterns of environmental stimuli. The return of many fish to the stream of their origin is to be expected, according to this viewpoint, because the patterns of environmental conditions which direct them persist year after year.

Variations of these views may be found expressed under different interpretations of the "parent stream" or "home stream" theory developed by investigators working on salmon migration. An excellent review of major problems and controversial questions in salmon migration is afforded by the symposium, "The Migration and Conservation of Salmon," published in 1939 by the American Association for the Advancement of Science.

SENSORY BASIS OF ORIENTATION

Whether the migratory fish has purpose and seeks its native stream or whether the fish is entirely directed by immediate environmental factors along its route, its orientation must be achieved by some sensory means.

With fish migration, as with bird migration, there has been much speculation over the possible existence of a special sensory perception that is unknown at present. No physical basis for this has ever been found nor have such sensory abilities ever been demonstrated. There is evidence that fish can see, hear, taste, and smell. It is known that they can respond to tactile and kinesthetic stimuli, react to acceleration and nonrectilinear motion, and maintain equilibrium. It has been demonstrated that they can respond to temperature and to various chemical substances by means other than taste or smell. In the absence of any evidence to the contrary, it is reasonable to suppose that these sensory abilities are the ones by which fish are guided while on their migrations. Therefore, it appears logical to explore fully the relation between these known sensory abilities and prevailing environmental patterns before considering hypothetical sensory abilities.

RELATION OF SENSORY ABILITIES TO ENVIRONMENTAL PATTERNS

As the sensory abilities of fishes have been revealed and delineated many investigations have been made to examine their relation to migration. Chidester (1924)[1] pointed out the number and diversity of these investigations as well as their apparently contradictory evidence.

Attention was turned to natural environmental patterns which might have a directional influence upon fish with the known sensory abilities. The physical and chemical gradients which exist along the migration paths of anadromous fishes were examined for their possible role in orienting migrating fish.

The observations of Ward (1920) in Alaska led him to believe that temperature was an important factor in the choice of a spawning stream by sockeye salmon, *Oncorhynchus nerka*. He observed that on the upstream migration the fish pass from swift to slow water and vice versa, that they go from shallow to deep water and vice versa, and that they move from turbid to clear water and vice versa. However, he found that at the junction of two streams the sockeye salmon consistently chose the colder stream and he concluded that temperature was the chief orienting factor.

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[1] For references referred to parenthetically, see Literature Cited, p. 395.

The earlier investigations of Chamberlain (1907) in Alaska also indicated that temperature influenced the selection of streams by sockeye salmon. However, Chamberlain found that the sockeye chose the warmer streams.

Foerster (1929) observed the migration of sockeye salmon near Cultus Lake, British Columbia, and found the sockeye at one time entering the colder stream and at another time selecting a warmer stream. He concluded that temperature probably had very little directing influence on the upstream migration of the sockeye salmon. Foerster also made measurements of the *p*H and of the dissolved oxygen in the streams, but was unable to find any correlation between variations in these factors and the selection of streams by the sockeye salmon.

Roule (1933) expressed the opinion that the direction of shad, *Paralosa nilotica rhodanensis* and *Alosa alosa*, migration was controlled by temperature. He pointed out that the migration begins when the river water, pouring into the sea in estuaries, is at a higher temperature than that of the sea. Roule related that in one section of the Rhone River shad fishermen always set their traps on only one bank of the river, whereas along most of the river they set traps on both banks. Investigation revealed that the water on one side of the river was several degrees warmer than on the other due to the influence of a warm tributary upstream. The shad were always found migrating on the warmer side; and they were also observed to turn off the main stream into certain tributaries which were warmer than the main stream. Roule's observations on the behavior of salmon, *Salmo salar*, during migration convinced him that the salmon were indifferent to temperature.

Roule (1914), observing the selection of particular streams by the Atlantic salmon, *Salmo salar*, in its upstream migration to spawning areas, concluded that the proportion of dissolved O_2 in the water was the dominant factor in directing the migration. He maintained that the salmon always choose the water with a higher concentration of dissolved O_2. Roule (1933) suggested that the metabolic condition of the fish results in increased respiratory activity and it becomes polarized toward the more highly oxygenated water. Roule used the word "branchiotropism" to describe deviations in direction brought about by respiratory influences. He maintained that the "branchiopolarity" of the salmon drives it forward and acts as its guide.

Chevey, Roule, and Verrier (1927) blamed the depletion of salmon runs in certain streams on the lack of dissolved O_2 in the streams owing to mill wastes. Their investigations indicated that salmon would not enter a stream with a low dissolved O_2 content. The observation that the shad, *Alosa alosa*, were not affected by the low O_2 content of the water pointed to a marked species difference.

Russell (1934) did not agree with the findings of Roule and his coworkers. He pointed out that in the mouths of certain salmon rivers, such as the Tees and the Tyne, there is a long stretch of heavily polluted water in which the O_2 content may fall very low. However, salmon enter and ascend these rivers.

Shelford and Powers (1915) using a gradient tank technique, found that herring fry, *Clupea pallasi*, would orient to differences in temperature and dissolved gases. Powers became convinced that gradients of CO_2 tension exert an important influence upon the orientation of migrating fishes. Powers and Hickman (1928) measured the CO_2 tension in lakes, in rivers draining lakes, and in rivers which did not drain lakes in the Fraser and the Columbia River systems. They found that, in general, lakes and rivers draining lakes had a lower CO_2 tension (average 0.57 mm. Hg) than rivers not fed by lakes (average 1.05 mm. Hg). Further analysis of the data also indicated that typical mountain streams had higher CO_2 tensions than streams of the lowland.

Powers (1939) pointed to an observation that the sockeye salmon, given a choice, will always choose the fork of a river which drains a lake. The chinook salmon, *Oncorhynchus tshawytscha*, in the same situation apparently is indifferent and moves up either branch. Powers suggested that the sockeye is responding to differences in CO_2 tension in its selection of a stream draining a lake. The lack of a similar response on the part of the chinook salmon was presumably looked upon as a species difference.

The publications of these investigators who were seeking to correlate the observed movements of migratory fishes to gradients of temperature and of dissolved gases were received with great interest. There has been, however, a general reluctance on the part of many engaged in fishery research to accept some of the conclusions put forth. Those investigators who were convinced of a highly developed homing ability in anadromous fishes found it difficult to reconcile the idea of migrating fishes responding to environmental gradients with that of homing. Many contradictory observations made by other workers in the field, because of a general tendency to avoid negative reporting, seldom reached the literature. Furthermore, field workers who were aware of the enormous difficulties in making dependable observations of the movements of fish in large rivers and streams, particularly with only intermittent observations made over a wide area, felt that the evidence upon which the conclusions were based was inadequate.

In summarizing previous research in this field it might be said that—

(1) The ability of fishes to detect differences in temperature and in amounts of dissolved gases has been established experimentally.

(2) Laboratory (gradient-tank) experiments have also established that differences in temperature and in amounts of dissolved gases can influence the direction of fish movement.

(3) Differences in water temperature and amounts of dissolved gases have been shown to exist in natural waters at points where they might exert an important influence upon the direction of migrating anadromous fishes.

(4) It has been suggested that these physical and chemical differences do influence the orientation of the migrating fish.

(5) Some field observations of migratory-fish behavior appear to show a relation between the direction of migration and gradients of certain physical and chemical factors. These field observations are relatively few, inconclusive, and contradictory.

Thus, it is known that some fishes can orient with reference to certain physical and chemical differences in water, but whether migrating anadromous fishes actually do orient with reference to such differences is not known. The following experiments were undertaken to explore this question with one type of anadromous fish.

EXPERIMENTAL APPROACH

In studying the influence of gradients of physical and chemical characteristics of water upon the orientation of migrating anadromous fishes a direct experimental approach was used. Experiments were undertaken which attempted to measure the directional responses of migrating fishes of the genus *Pomolobus* to certain differences in water characteristics including temperature, *p*H, and amounts of dissolved gases (O_2, N_2, and CO_2).

The experiments were designed to avoid many complications that have to be considered in laboratory experiments with live fish. The experiments were made in the stream in which the fish were migrating so that the fish would not be handled or subjected to the shock of being removed from their natural environment. Tests were made on thousands of fish, and each fish was tested only once so that considerations involving learning could be ignored.

Inasmuch as the special migratory behavior of anadromous fishes is exhibited for only limited periods of time, perhaps only once or twice during the life of the fish, an essential condition of these experiments was that they were conducted while the fish were actually migrating. The importance of this is realized when one considers how greatly the response of a fish to environmental stimuli may differ at various physiological stages of its life. As fingerlings, the fish are found migrating downstream; as maturing adults, they migrate upstream. In those species which survive spawning, the spent fish again migrate downstream. Frequently, individual fish of the same species may be found in a stream responding in very different ways to identical environmental stimuli.

The differences in physical and chemical factors tested were artificially produced in these experiments but the type and magnitude of the differences were within the range commonly found at stream junctions in nature.

MATERIALS AND METHODS

The experiments were conducted in the Herring River at Bournedale, Mass., in 1949 and 1950 during the spring herring runs. The herring run at Bournedale actually consists of two overlapping runs of closely related species. The earlier run, made up of alewives, *Pomolobus pseudoharengus* (Wilson), begins about the first of April and continues until the end of May. The second and smaller run of glut herring, *Pomolobus aestivalis*

(Mitchill), usually starts about the last week of May and lasts until the middle of June.

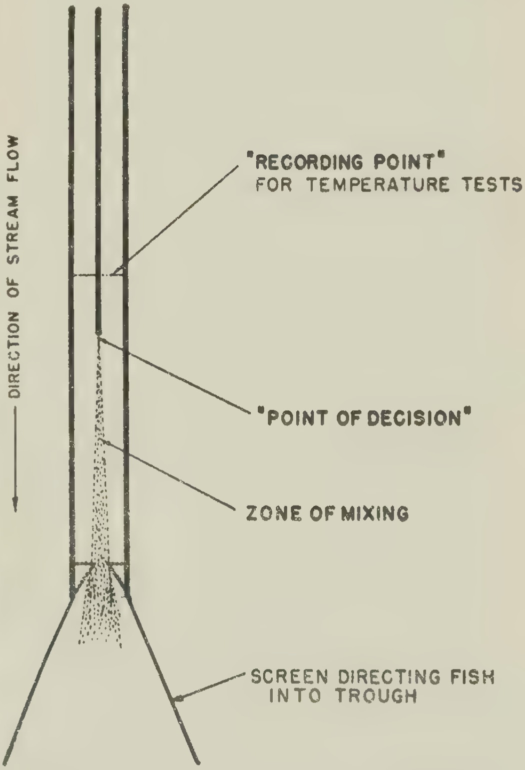
There are visible external differences by which these two species can be identified. The glut herring is generally smaller than the alewife, has a smaller eye in relation to the head, and when examined out of water has darker dorsal pigmentation. The individual variations in size within the two groups overlap considerably, and in the water each species has the ability to modify its pigment to blend with the background in the matter of a few seconds. Consequently, it is very difficult to distinguish between the two species with any degree of certainty without first removing the fish from the water. Attempts to separate the two species while the experiments were in progress proved to be impractical. When the studies were completed, a careful comparison of the responses shown by the fish in experiments conducted at the beginning of the early run when only alewives were present with those in experiments made near the end of the later run when only glut herring were present, failed to reveal any differences between the responses of the two species.

These anadromous members of the herring family (Clupeidae) proved to be ideally suited to experimental purposes. They are small and migrate in enormous numbers through easily accessible brooks and streams (fig. 1). The construction of the experimental apparatus and the conditioning of water for experiments with these fishes can be done on a smaller, less expensive scale than would be necessary for fishes such as the shad or the salmon. At Bournedale each year during the herring run, more than half a million of these fishes enter the small Herring River (completely fresh water; average flow less than 20 c. f. s.) from the sea water of the Cape Cod Canal and migrate upstream for approximately a mile to their spawning grounds in Great Herring Pond. The experiments were conducted in the stream a short distance below its entrance into Great Herring Pond.

Figure 1.—The herring run at Bournedale, Mass. This pool is immediately below the experimental station.

EXPERIMENTAL METHOD

As the fish migrated upstream, they were directed by wire screens into a shallow experimental trough. The upstream end of the trough was divided into two channels of equal size (fig. 2). As a fish progressed upstream through the experimental trough, it was presented with a choice between the two channels. Differences in water



DIRECTION OF STREAM FLOW
"RECORDING POINT" FOR TEMPERATURE TESTS
"POINT OF DECISION"
ZONE OF MIXING
SCREEN DIRECTING FISH INTO TROUGH

Figure 2.—Diagram of experimental trough. Dimensions: 18 ft. long, 21 in. wide, and 10 in. deep.

temperature, in pH, and in dissolved gases between the two channels were created experimentally. The influence of these differences in the physical and chemical characteristics of water upon the orientation of the migrating fish was measured by the number of fish choosing each channel.

The experimental trough was 21 inches wide, 10 inches deep, and 18 feet long. It was open at both ends so that when it was alined with the direction of stream flow and partially submerged, the water flowed freely through it. The two channels in the upstream end of the trough were 10 feet long and 10 inches wide. A 10-inch channel width was chosen because it was approximately equal to the length of the fish and would allow enough room for normal swimming movements and turning. The experimental trough could be raised or lowered in the water in order to create any desired depth of flow regardless of the natural fluctuation in the water level of the stream. The flow of water through the trough was maintained at a depth of 6 to 8 inches, while the velocity of water through the trough varied, depending on stream conditions, from a minimum of 1 foot a second to a maximum of 2 feet a second.

The trough was stained a dull mahogany to provide a dark background for the fish so that their behavior would be as natural as possible. Exploratory tests the previous year had shown that a light background made the fish extremely nervous and excitable when they were in the shallow water and confinement of the experimental trough. The trough was also placed in the stream several weeks before tests were begun to reduce the possibility of odors, or other factors that might be unfamiliar or objectionable to the fish.

To prevent light inequalities between the two channels resulting from shadows, the experimental trough was shaded from direct sunlight by a canvas canopy (fig. 3).

At the downstream end of the trough a wire-screen gate was installed to control the entrance of the fish into the experimental trough. The necessity for such a device became apparent during preliminary exploratory tests in which the entrance of the fish was unrestricted. When several fish entered at the same time, they frequently exhibited a schooling tendency and all followed the choice of the leader. Their behavior was such that it seemed probable that only one decision was actually made for the entire school. There were instances of schools splitting, with all those on the left side entering the left channel, and all those on the right side entering the right channel, suggesting that perhaps in these cases spatial relations alone were involved. There were many variations in such group behavior and they were difficult to interpret in a quantitative way. To avoid the problem completely, an entrance gate was designed. Through this gate (figs. 4 and 5) the fish were allowed to enter, one at a time, and only after the previous one had made its decision and was completely out of the trough.

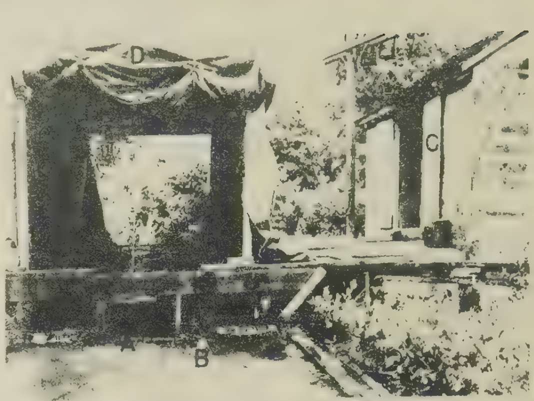


FIGURE 3.—General view of experimental station, Herring River, Bournedale, Mass., 1950.

A. Entrance for upstream migrants.
B. Bypass exit for downstream migrants.
C. Laboratory for chemical determinations.
D. Light-control arrangement.

The entrance gate also served to center the fish so that as it entered the experimental trough it was subjected to a mixture of the waters of both channels. Thus, the fish started in the center of a strong transverse gradient (fig. 2) and almost any lateral movement resulted in its being subjected to water of a different quality.

PROCEDURE

As the fish progressed upstream in the trough to the point where it had to choose between the two channels (the "point of decision" in fig. 2), it usually moved from one side of the trough to the other, alternately approaching each channel until it finally entered one. In those tests in which both channels were completely unobstructed the choice was recorded when the fish had completed

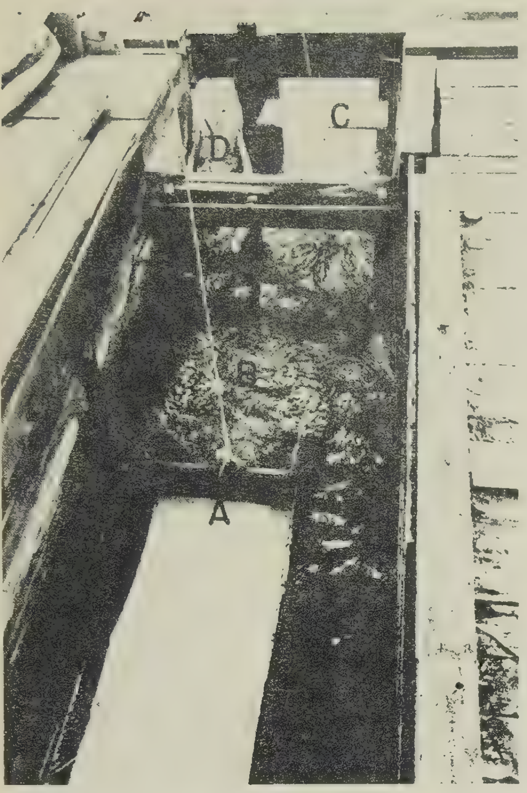


FIGURE. 4.—Entrance to experimental trough.

A. Entrance gate (closed).
B. Retaining pool.
C. Retaining-pool gate (open).
D. Bypass for downstream migrants.

(The white cloth on the bottom of the trough was for photographic purposes and was not present during the tests.)

its passage through the channel and was entirely clear of the trough. This system of recording decisions permitted the fish to change its choice of channels at any stage of its progress by turning back and entering the other channel.

During the experiments in which the water was being modified by heating, the reluctance of the fish to pass through the heating apparatus in the upstream ends of the channels, resulted in considerable delay. To save time a "recording point" (fig. 2) was chosen below the heating apparatus. When this arbitrary point which was 20 inches (approximately twice the length of the fish) from the entrance to the channel was reached, the fish was considered to have made its decision and the result was recorded. When once the fish had passed the recording point if its forward progress was too slow, it was urged to continue on out of the trough by taps on the trough with a stick immediately behind the fish. When the fish was completely out of the trough, the entrance gate was raised again to allow another to enter.

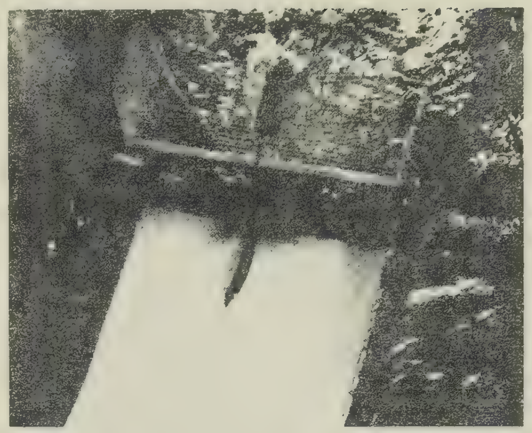


FIGURE 5.—Entrance gate. The fish were allowed to enter, one at a time, through a screen gate (shown open).

(The white cloth was not present during the tests.)

Before each series of tests, any necessary adjustments of experimental conditions were made and water samples and temperature measurements were taken. The fish were then allowed to enter the trough one at a time. It usually was found convenient to run approximately 25 to 30 individual tests in succession before the measurements were taken again. The average time for such a series of tests was about 40 minutes, although it fluctuated considerably depending upon the behavior of the fish.

CONTROLS

Every effort was made to keep conditions, e.g., light, depth of water, rate of flow, turbulence, as uniform as possible in both channels so that any directional response would be due solely to the factor being tested. Whenever major adjustments in the experimental conditions had been made, before tests with modified water were begun, a series of control tests was run to ensure that such uniform conditions prevailed. The results of these tests are summarized in table 1.

TABLE 1.—*Daily totals of control tests made to ensure that uniform conditions existed in both channels of the experimental trough, 1949*

Date	Number of fish entering—	
	Left channel	Right channel
April 30	91	89
May 1	49	39
2	54	48
3	68	73
7	97	91
8	58	49
11	19	15
12	20	22
14	71	54
15	81	83
16	49	47
19	25	29
22	59	49
23	47	58
24	24	24
30	29	30
Total	841	800
Percent	51.3	48.7

To minimize the possibility of some unrecognized factor influencing the choice of the fish, control and test channels were alternated between each series of tests. Such alternation resulted in any "nonalternating" influence being cancelled out when the figures were totaled. An example of the pattern of controls and tests is given in table 2.

TABLE 2.—*Example of the pattern of controls and tests, May 15, 1949*

[Tests listed in chronological order]

Left channel		Right channel	
Water characteristic [1]	Number of fish	Water characteristic [1]	Number of fish
Control	18	Control	17
CO_2	11	Control	31
Control	26	CO_2	19
Control	25	Control	27
Control	35	CO_2	12
CO_2	11	Control	34
Control	16	Control	16
Control	33	CO_2	17
CO_2	9	Control	26
Control	22	Control	23
CO_2	8	Control	31
Control	31	CO_2	14

[1] Control, water unmodified; CO_2, gaseous CO_2 added.

During tests involving temperature differences of greater than 1 degree centigrade, it was necessary to have a greater number of heaters in one channel than in the other. To be certain that the response shown was the result of temperature differences rather than differences in hydraulic conditions created by the unequal distribution of heating apparatus, a series of control tests was run with the heaters in place but with the power turned off. The results of the control tests which were interspersed with the actual temperature tests are shown in table 3. They indicate that the presence of the nonoperating heaters had little or no effect upon the choice of channels made by the fish.

TABLE 3.—*Control tests during temperature experiments, 1950*

[Immersion heaters in place but power turned off]

Date and time	Number of fish entering—		Number of immersion water heaters in—	
	Left channel	Right channel	Left channel	Right channel
May 13, 3:45 p. m.	16	17	5	5
14, 6:25 p. m.	27	25	0	10
15, 8:00 a. m.	9	8	0	11
20, 10:00 a. m.	12	12	0	11
24, 2:30 p. m.	13	14	0	11
24, 3:30 p. m.	14	13	0	11
25, 4:00 p. m.	26	27	0	11
26, 9:15 a. m.	15	12	0	11
26, 11:30 a. m.	12	15	0	11
27, 10:30 a. m.	21	30	0	8
27, 11:55 a. m.	9	10	0	8
27, 1:30 p. m.	11	15	0	8
27, 4:00 p. m.	8	7	0	8
27, 5:00 p. m.	27	34	0	8
28, 12:40 p. m.	13	12	0	8
28, 2:00 p. m.	13	11	0	8
28, 5:30 p. m.	13	12	3	8
June 3, 8:15 a. m.	7	5	0	11
6, 10:30 a. m.	4	4	0	11
7, 11:15 a. m.	13	15	0	11
Total	283	298		
Percentage	49	51		

WATER MODIFICATION

Temperature

The modification of the water temperature was accomplished by the use of industrial electrical immersion water heaters. These heaters (32 a., 7.5 kw., 230 v.) were of the tubular type and shaped in a simple loop so as to fit easily into the channels of the experimental trough (fig. 6). Each of the 11 heaters was connected separately to the main circuit and could be turned on or off at will without interfering with the operation of any of the other heaters. The arrangement was simple and flexible and made a graded control of temperature possible.

Gaseous Content

The gaseous content of the water was modified by the introduction of specific gases. These gases (O_2, N_2, and CO_2) were bubbled into the water at the upstream end of the trough directly in front

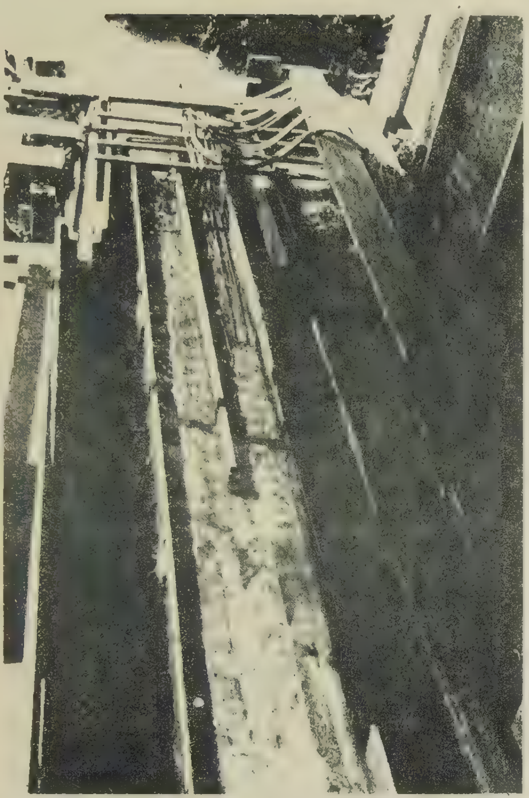


FIGURE 6.—Upstream end of experimental trough during temperature tests. All immersion water heaters are in place for maximum temperature difference.

(Shade on left was raised to allow light for photographic purposes. During the experiments no shadows were present.)

of the channel or channels in which the water was to be modified.

The device used to accomplish this (fig. 7) consisted of two batteries of porous-stone aerators of the type commonly used in small aquariums. Each battery of aerators produced a band of very fine bubbles. The incorporation of two separate batteries in the same device made it possible to modify independently the water of both channels at the same time.

Nongaseous Chemicals

The nongaseous chemicals used to modify water in experiments were first dissolved in a carboy of water from the stream. They were then introduced at a controlled rate into the upstream end of one of the channels through a colorless plastic tube positioned horizontally an inch above the floor of the trough at right angles to the direction of stream flow. Small holes were bored in the plastic tube at short intervals to allow an even distribution of the carboy liquid throughout the channel.

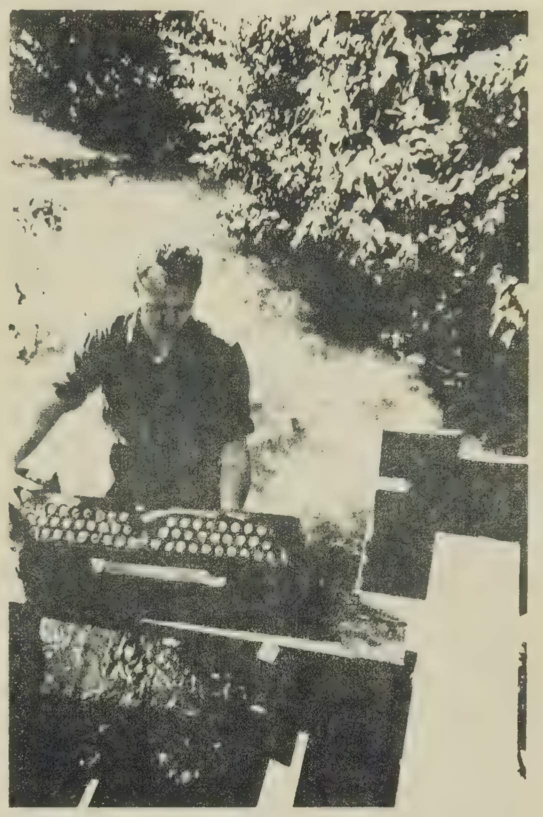


FIGURE 7.—Device for modifying gaseous content of water. The device contained two separate batteries of aerators so that the two channels could be modified independently at the same time.

MEASUREMENTS

Water Samples

Water samples were collected in wide-mouthed 100-milliliter bottles at the downstream end of each channel. Sample bottles were stoppered while still under water to avoid any gaseous exchange with the air. The samples were collected simultaneously in both channels and were immediately brought into the field laboratory where the chemical determinations were begun at once.

Titrations

Titrations were done with a Beckman pH meter. The water-sample bottles were calibrated with the solid stoppers on so that the exact amount of water in each sample was known without further measurement. The titrations were performed in the sample bottles to avoid any opportunity for the modification of the gaseous content of the water due to exposure to air in pouring.

Hydrogen-ion Concentration

Measurements of hydrogen-ion concentrations were made to within 0.03 pH unit with a Beckman pH meter. A Hellige pocket color comparator was used for rapid pH measurements (to within 0.1 pH unit) during adjustment of valves while setting up experimental conditions and during a number of the earlier exploratory experiments.

Alkalinity and HCO_3.

In the range of pH in which the experiments were made (pH 7 to pH 6) the alkalinity was assumed to equal the concentration of HCO_3. Methyl-orange alkalinity was measured (American Public Health Association 1946) by titrating the sample with H_2SO_4 to an end point of pH 4.4.

Carbon Dioxide

The free, or uncombined, CO_2 content of the water was measured in two ways. Some of the measurements were made directly by titration of the sample with NaOH (American Public Health Association 1946) to an end point of pH 8.2. Other determinations of free CO_2 were made indirectly by measuring alkalinity (methyl orange) and pH and then determining CO_2 by the graphic method of Moore (1939). The measurements were made to within 0.1 p. p. m. CO_2. Those measurements made directly by titrating with NaOH were slightly lower than the measurements made indirectly by the graphic method. Therefore, in comparing the water of the two channels only one method was used for each pair of measurements. The range of conditions under which the measurements were made is indicated by figure 8 which shows CO_2 measurements made during the experiments.

During the series of tests which examined the orientative influence of CO_2, water was modified by the introduction of gaseous CO_2. Addition of gaseous CO_2 to the almost unbuffered water of the stream produced several effects. It increased the concentration of free CO_2 and it decreased the pH. It also raised the partial pressure, or tension, of CO_2 in the water. Examples of data from individual tests (table 4) illustrate the first two of these effects. It will be noted that the concentration of HCO_3 was largely unaffected. In the range of pH in which the experiments were made (pH 7 to pH 6), carbonates were not present.

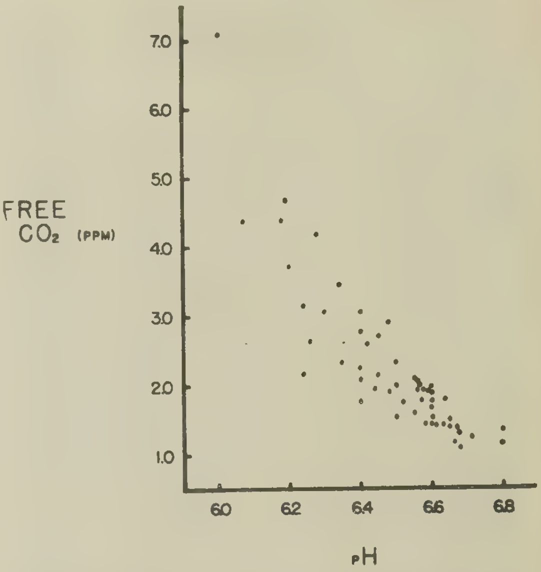


FIGURE 8.—Free CO_2 measurements, May 1950. Only measurements of samples of unmodified stream water and water modified by the addition of gaseous CO_2 are included. The samples were taken under a wide variety of stream and weather conditions.

Water was modified by addition of $K_2H(PO_4)$ during the tests of the orientative influence of pH. Examples of data from individual tests are given in table 4. In these tests the changes in pH were of approximately the same magnitude as the changes in pH in the tests in which CO_2 was added (although $K_2H(PO_4)$ raised the pH while CO_2 lowered it). The addition of $K_2H(PO_4)$, however, had much less effect upon the concentration of free CO_2.

During this investigation, measurements of CO_2 were restricted to the convenient and widely accepted methods available for measuring the amount of free CO_2. The importance of measuring dissolved gases in terms of partial pressures

TABLE 4.—*Examples of chemical measurements made during individual tests, June 11, 1950*

[Stream temperatures, 19° to 19.4° C.]

Channel	Water characteristic[1]	Hydrogen-ion concentration	Alkalinity or HCO_3	Carbon dioxide
			P. p. m. Ca CO₃	*P. p. m.*
Left	CO_2	6.40	4.04	3.05
Right	Control	6.57	3.98	2.06
Difference		.17	.06	.99
Left	Control	6.57	3.88	1.95
Right	CO_2	6.18	3.76	4.08
Difference		.39	.12	2.73
Left	$K_2H(PO_4)$	6.52		[2] 1.70
Right	$K_2H(PO_4)$	6.97		[2] 1.62
Difference		.45		.08
Left	$K_2H(PO_4)$	6.94		[2] 1.71
Right	Control	6.57		[2] 1.78
Difference		.37		.07

[1] CO_2, gaseous CO_2 added; control, water unmodified; $K_2H(PO_4)$, $K_2H(PO_4)$ added.

[2] Samples titrated with NaOH.

when considering their physiological effects upon organisms is recognized. The ability of a gas to diffuse through a membrane depends upon the tension of the gas in solution. Therefore, the tension of the gas is critical where, as in respiration, an actual gaseous exchange is made. However, very little is known of the sensory mechanism by which fish detect differences of CO_2; nor is it known whether CO_2 must actually permeate a membrane to affect the sensory organs. Under the circumstances of these experiments, where both channels receive water from the same source under identical conditions, the CO_2 tension would be directly proportional to the amount of free CO_2 present. Therefore, the relative amounts of CO_2 in the two channels may be used as indexes of the relative CO_2 tensions.

Oxygen

The amount of dissolved oxygen was determined by the standard Winkler method (American Public Health Association 1946) after preliminary orientation tests (Ellis, Westfall, and Ellis 1948) for the presence of interfering substances proved to be negative.

Temperature

Temperatures were measured to 0.1° C. by the use of a mercury thermometer held horizontally in the water with its long axis in the direction of the current. The measurements were taken at the downstream end in each channel with the center of the thermometer at a point 2 inches from the bottom of the trough (the level at which the fish usually swam) and 2 inches from the wall which divided the trough into two channels.

Velocity

The velocity of the water flowing through the trough was measured by means of an impeller-type current meter. Measurements were accurate to within 0.2 feet per second, and represent the average velocity of the water over a 90-second period of time. The measurements were taken at the downstream end of each channel at a point halfway between the channel walls.

ABERRATIONS IN EXPERIMENTAL CONTROL

Throughout the experiments, measurements of physical and chemical water characteristics such as temperature, velocity, *p*H, and amounts of dissolved gases were much more precise than the experimental control of these characteristics. Hydraulic conditions above the head of the experimental trough created a periodic eddying (every 5 to 15 seconds) which resulted in a fluctuation in the rate of flow alternately in each channel. During tests in which water characteristics were being modified, eddying caused a periodic fluctuation in the degree of modification. For example, during tests in which the water was modified by heating, eddying resulted in a temperature fluctuation of approximately 0.5° C. in the channel being modified.

Temperature measurements to within 0.1° C. were made almost instantaneously, and the extent of the temperature fluctuation was easily measured by a comparison of maximum and minimum temperature readings. However, measurements of other water characteristics such as velocity, *p*H, and amounts of dissolved gases were average measurements. Velocity measurements (read in terms of propeller revolutions per unit time) represented an average velocity for a 90-second period of time. The manner in which the water samples were taken for measurements of *p*H and amounts of dissolved gases tended to collect a mixture of the water flowing through a channel over a period of time greater than the time for a complete cycle of eddy fluctuation and so these measurements also represent measurements of average conditions.

Such average measurements gave no clear indication of the degree of fluctuation.

Some of the other experimental conditions also could not be controlled completely. The depth of the water in the trough, maintained at 6 to 8 inches at the downstream end of the two channels, varied from 4 inches to 10 inches at the ends of the trough when the trough deviated from a horizontal position. The downstream end of the trough had a tendency to settle as a result of the clogging of the screen entrance gate by floating organic debris. Variations of this sort affected the channels equally, however, and probably are of little significance.

During the experiments in which water was heated electrically there frequently was a vertical variation in the temperature of the water in the modified channel due to inadequate mixing of the heated water. This was particularly true when only a few heaters were in operation. At such times, the variation was as much as 0.4° C. from the warmer water near the bottom of the channel to the cooler water near the surface. The temperature measurements, made 2 inches from the bottom of the channel (the level at which the fish usually swam), were always of the maximum temperature.

In interpreting the data collected during these experiments, such variations in experimental conditions must be taken into consideration, particularly when thresholds are concerned. The thresholds for the responses of the fish may actually be lower than those indicated by the data.

EXPERIMENTS

ORIENTATIVE INFLUENCE OF TEMPERATURE

Experiments were conducted in which the migrating fish were presented with a choice between waters of two different temperatures. The responses of the fish (table 5) indicated a preference for the warmer water.

The stream temperature during these experiments ranged from 11.1° to 22.3° C. The temperature differences between channels, created by heating the water of one channel, were varied from 0.4° to 3.0° C. The threshold of the response appeared to be at a temperature difference of approximately 0.5° C.

Periodic eddying which caused a fluctuation in the water temperature of the channel being modified (see Aberrations in Experimental Control, p. 385) was probably responsible for the apparently intermediate nature of the response to temperature differences of 0.5° to 1.0° C. The temperature difference values given in tables 5 and 6 are maximum values. The minimum values were approximately 0.5° C. less. For example, during tests at the recorded temperature difference of 0.7° C., for at least part of the time, the temperature difference was approximately 0.2° C.

Therefore, only at recorded temperature differences above 1.0° C. was the threshold difference of 0.5° C. exceeded continually throughout the entire test.

TABLE 5.—*Response to temperature differences as shown in experiments of May 7 to June 8, 1950*

[Stream temperatures, 11.1° to 22.3° C.]

Water temperature difference between channels [1] (Centigrade)	Number of decisions	Entered channel with—	
		Warmer water	Cooler water
		Percent	*Percent*
0.4°	98	[2] 49	51
0.5°	109	57	43
0.6°	51	61	39
0.7°	180	63	37
0.8°	427	60	40
0.9°	471	61	39
1.0°	76	63	37
Total	1,314	[3] [4] 61	39
1.1°	22	77	23
1.2°	98	80	20
1.3°	136	76	24
1.4°	100	76	24
1.5°	142	77	23
1.7°	98	79	21
1.8°	107	80	20
1.9°	27	78	22
2.0°	83	80	20
Total	813	[3] 78	22
2.2°	213	73	27
2.3°	132	73	27
2.4°	108	83	17
2.5°	28	75	25
2.7°	24	79	21
3.0°	12	75	25
Total	517	[3] 76	24

[1] Temperature differences are maximum values. Minimum temperature differences were approximately 0.5° C. less.

[2] No response.

[3] Response.

[4] See notes on eddying phenomenon, p. 385.

Taking the eddying into account, the intermediate nature of the response to temperature differences from 0.5° to 1.0° C. should probably be discounted and considered as due to imperfect experimental conditions. The data would then be interpreted as describing a uniform ungraded response to temperature differences greater than the threshold.

RELATION OF TEMPERATURE RESPONSE TO TEMPERATURE LEVEL

Tabulation of experimental data according to stream temperature levels (table 6) revealed a general tendency for the response to temperature differences between 0.5° and 1.0° C. to decrease as the temperature level of the stream increased. When the temperature differences between channels were greater than 1.0° C., the temperature level of the stream had no discernible influence upon the response of the fish.

TABLE 6.—*Relation of temperature response to temperature level*

[Retabulation of data from table 5. Stream temperature levels include +0.9° C. (e. g., 11° C. includes temperature levels to 11.9° C.)]

Stream temperature level	Number of decisions	Entered channel with—	
		Warmer water	Cooler water
Group A:[1]		*Percent*	*Percent*
11° C	139	65	35
12° C	178	65	35
13° C	185	65	35
14° C	274	60	40
15° C	116	59	41
16° C	124	55	45
17° C	66	55	45
18° C	85	54	46
19° C	147	53	47
Group B:[2]			
11° C	35	80	20
12° C	43	79	21
14° C	238	77	23
15° C	217	80	20
16° C	159	75	25
17° C	290	76	24
18° C	198	77	23
20° C	123	82	18
22° C	27	78	22

[1] Temperature difference between channels, 0.5° to 1.0° C.
[2] Temperature difference between channels, 1.1° to 3.0° C.

Taking into account once again the eddying condition (see p. 385), the data indicate that the responses of the fish were affected by the temperature level only when temperature differences of threshold magnitudes were concerned. The evidence suggests a possible relation between this phenomenon and the type of threshold phenomena described by Weber's law. Weber (1846) believed the threshold of difference to be proportional to the intensity of stimulus. Although the ratio of these two factors has since been shown to be variable, a tendency for the threshold of difference to increase with an increase in intensity of stimulus has been observed. The experiments at Bournedale, planned with other purposes in mind, did not produce the type of data necessary to examine this particular aspect of the response to temperature differences. However, it seems very probable that the decrease in the response of the fish (shown in group A, table 6) was due to an increase in the threshold of the response to temperature differences as the temperature level of the stream increased.

ORIENTATIVE INFLUENCE OF CO_2

The migrating fish were presented with a choice of waters having different amounts of free, or uncombined, CO_2. The difference in free CO_2 between the waters of the two channels was established by the direct addition of gaseous CO_2 to the water of one channel while the other remained unmodified. During some of the tests this procedure was varied by the addition of the gaseous CO_2 to both channels but at different rates. Throughout the tests the fish indicated a definite preference for the water with the lower free CO_2 content (table 7).

TABLE 7.—*Responses to differences in CO_2 as shown in experiments, May 1–30, 1949, and May 7–June 9, 1950*

Free CO_2 difference between channels	Number of decisions	Entered channel with—	
		Lower CO_2	Higher CO_2
		Percent	*Percent*
>4.0 p. p. m.	1,120	73	27
1.4 p. p. m.	128	77	23
0.6 p. p. m.	663	71	29
0.3 p. p. m.	216	69	31
0.2 p. p. m.	157	59	41

NOTE.—Unmodified stream water varied from 0.7 p. p. m. free CO_2 to 2.9 p. p. m. free CO_2 and pH 6.9 to pH 6.4. Stream temperatures 11.1° to 22.3° C. CO_2 differences listed include differences ±0.1 p. p. m. of listed differences except 0.3 which includes only +0.1 p. p. m.

Whether the fish in the CO_2 experiments were responding to differences in free CO_2 or to associated differences in HCO_3 is not actually known. The data (table 7) indicate that if the response was to differences in the amount of free CO_2, the threshold of the response lies below differences of 0.3 p. p. m. If the response of the fish was to differences in HCO_3, then the threshold of the response must be much lower. During most of the tests in which the differences in free CO_2 were less than 1.0 p. p. m., the differences in HCO_3 were not even measurable by the method of measurement used (i. e., they were less than 0.1 p. p. m. HCO_3 as $CaCO_3$). It seems more probable that the response of the fish was a response to free CO_2.

The experiments do not indicate whether the response of the fish (assuming that the response was to free CO_2) was to differences in the amount of free CO_2 or to differences in CO_2 tension. The difference in CO_2 tension associated with a difference of 0.3 p. p. m. free CO_2 under the conditions of these experiments would be approximately 0.1 mm. Hg.

The response of the fish to differences in CO_2 (whether it was to the amount of free CO_2, to the CO_2 tension, or to associated HCO_3) was similar to the response of the fish to temperature differences in that it appeared to be a uniform response to all differences above the threshold difference.

RELATIVE ORIENTATIVE INFLUENCE OF CO_2 AND TEMPERATURE

As the evidence was acquired indicating that differences in temperature and differences in CO_2 could influence the orientation of the migrating fish, the need for some information on the relative influence of the two factors became increasingly obvious. Under the controlled conditions of the experiments, where all factors other than the one used for testing were maintained equal in both channels, the fish might show as great a response to a relatively minor influence as they would to an important or dominant factor. To examine the relative orientative influence of CO_2 and temperature, two groups of experiments were undertaken. In one set of experiments the directional influences of the two factors were arranged so as to be in conflict. The differences in CO_2 favored the choice of one channel, while the differences in temperature favored the selection of the other. In a second group of experiments the differences both in CO_2 and in temperature favored the selection of the same channel.

The data (table 8) collected indicate that the relative importance of the two orienting factors depends upon their quantitative relationships. By altering the relative amounts of heat and of CO_2 added to the water, it was possible to demonstrate circumstances under which either factor could balance or even dominate the other when the factors were in opposition. The data also suggest that when the two factors are not in opposition they may actually augment each other and together provoke a response in a greater number of fish than either factor could produce alone.

ORIENTATIVE INFLUENCE OF pH

In the preceding experiments involving the addition of gaseous CO_2 to the water, the differences in the amount of free CO_2 between the two channels were always accompanied by differences in *p*H (see table 4). The question arises as to whether the response shown by the migrating fish is to the differences in CO_2 or to the accompanying differences in *p*H.

An attempt was made to answer this question experimentally with the migrating fish. It was necessary to use a substance which would, when added to the water, modify the *p*H of the water to the same degree that it was modified during the CO_2 experiments (see table 9) without, at the same time, materially affecting the amount of free CO_2 in the water. It was also necessary that the substance be one to which the fish would not respond by means such as taste or smell. To avoid the difficulties of determining whether the response of a fish was to the taste or to the smell of a chemical, or whether its response was to *p*H differences created by that chemical, it was necessary to select a substance to which the fish did not respond at all.

In one of a series of exploratory tests (table 10) NaOH was used to modify the water. There was no response to a difference in *p*H of 0.1 (compare with response to *p*H difference 0.1 created by the addition of gaseous CO_2, table 9). However, it will be noted that when the difference in *p*H was greater than 1.0 *p*H unit, the fish favored the

TABLE 8.—*Relative orientative influence of CO_2 and temperature as shown in tests made June 3–11, 1950*

Relation of factors	Water temperature difference between channels	Free CO_2 difference between channels	Number of decisions	Entered channel with—			
				Warmer water and higher CO_2	Cooler water and lower CO_2	Warmer water and lower CO_2	Cooler water and higher CO_2
	° *C.*	*P. p. m.*		*Percent*	*Percent*	*Percent*	*Percent*
Opposing	0.5 to 0.6	>7.0	99	24	76		
	1.8 to 2.1	0.5 to 2.0	129	62	38		
	1.8 to 2.4	2.4 to 7.0	169	48	52		
Augmenting	2.0 to 2.4	0.5 to 2.0	154			83	17

NOTE.—Stream temperatures, 16.9° to 22.2° C. Unmodified stream water, 0.7 p. p. m. to 2.1 p. p. m. free CO_2; pH 7.0 to pH 6.5.

TABLE 9.—*Experiments with CO_2 tabulated according to differences in pH, May 1949*

pH difference between channels [1]	Number of decisions	Percent entering—	
		Higher CO_2	Lower CO_2
>1.00	650	30	70
0.10	663	29	71
0.05	114	28	72
<0.05	157	41	59

[1] Range, pH 6.0 to pH 6.8.

TABLE 10.—*Experiments with NaOH tabulated according to differences in pH, May 24, 1949*

pH differences between channels	Number of decisions	Percent entering—	
		Control channel [1]	Channel with NaOH added [2]
>1.00	267	39	61
0.10	104	48	52

[1] Unmodified stream water, pH 6.6 to pH 6.8; low pH; high CO_2 content.
[2] High pH; low CO_2 content.

modified water. Although CO_2 was not measured in this test it seems very probable that the difference in free CO_2 which would be associated with the large difference in *p*H would exceed the threshold 0.3 p. p. m.

After several acids and bases were tried, an experiment was undertaken using $K_2H(PO_4)$ as the modifying agent. The data collected (table 11) reveal no indication of a response on the part of the fish although differences in *p*H were present. These differences in *p*H were of the same magnitude as those in many CO_2 tests in which the fish responded. The accompanying table 12 of free CO_2 measurements made while the tests were in progress shows that during the tests differences of free CO_2 between channels were very small, generally less than the precision of measurement.

TABLE 11.—*Orientative influence of pH as shown in tests made June 10–12, 1950*

[Differences in pH include differences ±0.1 pH unit]

$K_2H(PO_4)$ added	Unmodified control	Difference in pH	Number of decisions	Entered channel with—	
				High pH	Low pH
pH	*pH*			*Percent*	*Percent*
6.7	6.5	0.2	148	49	51
6.9	6.5	.4	127	51	49
7.1	6.5	.6	141	47	53
7.3	6.5	.8	20	50	50
Total			436	49	51

TABLE 12.—*Measurements of free CO_2 taken during the tests shown in table 11*

[Samples titrated with NaOH]

$K_2H(PO_4)$ added	Unmodified control	Difference in free CO_2	Difference in pH
P. p. m.	*P. p. m.*	*P. p. m.*	
1.94	1.96	0.02	0.2
1.62	1.69	.07	.3
1.71	1.78	.07	.4
1.62	1.70	.08	.4
1.31	1.45	.14	.6

On the basis of the evidence from this experiment, it would seem reasonable to conclude that the response shown by the migrating fish in the previous tests was a response to differences in CO_2 rather than a response to differences in *p*H.

EXPERIMENTS USING NITROGEN AND OXYGEN

Nitrogen

During the tests with CO_2, particularly those tests in which the CO_2 had been added to only one of the two channels, the possibility had to be considered that the physical presence of many bubbles in the modified channel might be influencing the choice of the fish. To eliminate this possibility nitrogen was used as a control. The gaseous nitrogen was bubbled into the water of one of the channels in the same manner and at the same rate as the CO_2 in the previous experiments. The addition of the N_2 produced no measurable difference in the amount of dissolved O_2. The data (table 13) reveal that the fish failed to show any response to the nitrogen or to the presence of the many bubbles produced. The nitrogen was then used as a control in a series of CO_2 tests. The results of these tests show the same response to CO_2 that was shown in previous tests, again indicating that the presence or absence of the bubbles had no influence upon the choice of the fish.

Oxygen

To investigate the orientative influence of O_2, the migrating fish were presented with a choice of waters which contained different amounts of dissolved O_2. The water of one of the channels was modified by the addition of gaseous O_2. The experiment, however, was severely limited by the fact that the water of the stream was already more than 100 percent saturated. The data in table 13 show that the fish did not respond to a relatively small difference in O_2 under these conditions. The

TABLE 13.—*Experiments testing orientative influence of oxygen and nitrogen*

Factor	Number of decisions	Entered control channel	Entered channel with—		
			N_2 added	CO_2 added	O_2 added
		Percent	*Percent*	*Percent*	*Percent*
Nitrogen bubbles	300	50	50		
Nitrogen (control)	477		71	29	
Oxygen [1]	344		50		50

[1] Stream temperature, 15.4° to 19.1° C. O_2 content of unmodified stream water, 10.5 to 10.7 p. p. m. O_2 difference between channels, 1.1 p. p. m.

experiments unfortunately provide no information on the possible effect of differences in O_2 at lower values where differences may be very important.

OTHER FACTORS INFLUENCING ORIENTATION

Although the major experimental efforts of this investigation were concerned with the orientative influence of temperature and dissolved gases, exploratory experiments also examined the influence of other factors.

The influence of water velocity upon the orientation of the migrating fish was explored by subjecting the fish to a choice between waters of different velocities. The difference in velocity between the two channels was created by placing a glass plate across the upstream entrance to one of the channels, restricting the amount of water entering that channel and so reducing the velocity of the water in the downstream end of the channel. The response of the fish (table 14) indicated that water velocity could be a factor in fish orientation.

The influence of water turbulence upon the orientation of the fish was explored in a similar manner. The turbulence in one of the channels was reduced by placing glass plates, several feet in length, in the center of the channel parallel to the channel walls. This produced a flow which was smooth and laminar in appearance. In the other channel, small glass plates were set at an angle to create eddies which produced a visible turbulence. Most of the fish selected the channel with less turbulence (table 15). CO_2 was then added to the channel with less turbulence in order to discover the relative influence of turbulence and CO_2. The data indicate that CO_2 had the greater orientative influence.

TABLE 14.—*Orientative influence of velocity*

Water velocity		Number of decisions	Entered channel with—	
Right channel	Left channel		Higher velocity	Lower velocity
Ft./sec.	*Ft./sec.*		*Percent*	*Percent*
1.5	0.7	26	85	15
0.7	1.0	26	65	35

TABLE 15.—*Orientative influence of turbulence and CO_2*

Influence of—	Number of decisions	Entered channel with—	
		Maximum turbulence	Minimum turbulence
		Percent	*Percent*
Turbulence	26	32	68
Turbulence and CO_2	27	70	[1] 30

[1] CO_2 added, 4 p. p. m.

An exploratory experiment was made which indicated that visual factors may influence fish orientation. The downstream end of one channel was partially blocked (see fig. 9). The fish normally swam within a few inches of the bottom of the trough so that the "obstacle" did not interfere in any physical way with their progress. However, most of the fish entered the channel which was completely unobstructed. To examine the relative influence of this visual factor and temperature, the water of the partially blocked channel was heated 2° C. The data (table 16) show that under these conditions temperature was the dominant orienting factor.

These tests were crude experiments of an exploratory nature. There undoubtedly were some velocity differences involved in the turbulence tests. The partial block at the downstream end of one of the channels in the tests involving the visual factor probably created slight differences

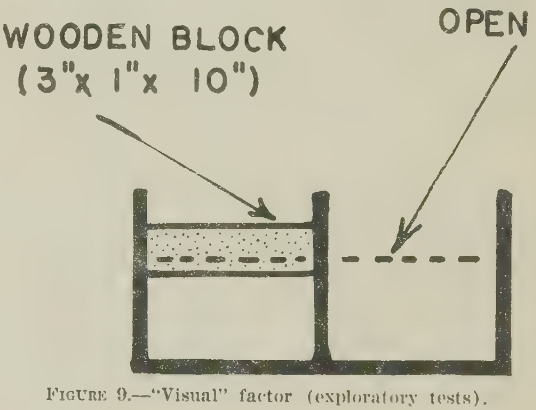


FIGURE 9.—"Visual" factor (exploratory tests).

TABLE 16.—*Orientative influence of the visual factor*

Influence of—	Number of decisions	Entered channel that was—	
		Open	Obstructed
		Percent	*Percent*
Visual factor	89	65	35
Temperature and visual factor	93	40	[1] 60

[1] Heat added, 2° C.

in hydraulic conditions between the two channels. The experiments were done with relatively small numbers of fish and the degree of the response should not be interpreted too literally. However, the experiments are presented here beause they do indicate that characteristics of flow, such as velocity and turbulence, can have a directional influence upon migrating fish. They also indicate that, under some circumstances at least, visual factors are capable of influencing fish orientation.

THE 3 : 1 RATIO OF THE RESPONSE

The explanation for the persistence of the approximately 3 : 1 ratio in the response of the fish to temperature differences and to CO_2 differences is not readily apparent. The absence of a response much closer to a 100 percent response under such controlled conditions would seem to indicate that only a proportion of the fish were influenced by the orienting factor. If, for example, half of the fish were influenced by the testing factor and the other half entered the channels at random, the resulting ratio would be 3 : 1.

A possible sexual variation in the response of the fish was considered. A trap was placed at the head of each channel and after a series of CO_2 tests had been run, the fish in each trap were examined for sex. This procedure was later repeated with a series of temperature tests. The data (table 17) indicate that the sex of the fish has no effect upon its response to differences in CO_2 and temperature.

The possibility of individual variation in the sensitivity of the fish to temperature differences and to CO_2 differences was examined by gradually increasing the differences between the two channels. Had there been significant individual variation in sensitivity, the response would have become greater as the difference between channels gradually exceeded the thresholds of more and more fish. This, however, did not occur. The response remained approximately 3 :1 even at the maximum attainable differences (>7.00 p. p. m. free CO_2 and 3.0° C.).

TABLE 17.—*Influence of sex on the response to CO_2 and temperature*

Factor and sex	Number of decisions	Percent that entered channel with—			
		CO_2 content—		Temperature—	
		Higher	Lower	Higher	Lower
CO_2:					
Male	54	26	74		
Female	70	27	73		
Temperature:					
Male	24			79	21
Female	38			76	24

The possibility was also considered that some individuals might be completely insensible to the differences in temperature and CO_2 which were being used in the experiments. An experiment was set up in which fish that had previously been tested were again subjected to the same choice. A trap was placed at the head of each channel and a series of CO_2 tests were made. The trapped fish were then brought back to the entrance of the experimental trough and the CO_2 tests repeated. The data (table 18) show that the response of the fish that had previously entered the channel with the higher CO_2 was approximately 3 : 1 in favor of the channel with the lower CO_2, and those fish which had previously entered the channel with the lower CO_2 also exhibited a 3 : 1 response in favor of the channel with the lower CO_2.

Such evidence strongly suggests that the 3 : 1 ratio is not due to the failure of particular individuals or particular groups of individuals to respond to the orienting factor. It seems more probable that the explanation lies in the behavior patterns inherent in all the fish. If, for example, every fish responded to an orienting factor only half the time and acted at random the other half, the result would also be a 3 : 1 ratio. Further

TABLE 18.—*Retesting the response of fish to CO_2*

Fish from channel with—	Number of decisions	Entered channel with—	
		Higher CO_2	Lower CO_2
		Percent	*Percent*
Lower CO_2	111	27	73
Higher CO_2	54	30	70

experiments may be necessary to throw some light on the nature of the ratio and to learn whether the phenomenon has any significance beyond the restricted circumstances of this experimental method.

DISCUSSION

When the results of the preceding experiments are compared with the findings of other investigators several interesting possibilities are suggested. One possibility is that the response of the fish to temperature differences might be a family characteristic. The two species of fish, *Pomolobus pseudoharengus* (Wilson) and *Pomolobus aestivalis* (Mitchill), which at Bournedale showed a consistent preference for warmer water, are members of the family Clupeidae. Shelford and Powers (1915) found that herring, *Clupea pallasi*, fry preferred warmer water. The observations of Roule (1933) indicated that migrating shad, *Paralosa nilotica rhodanensis* and *Alosa alosa*, which also belong to the family Clupeidae, selected water of higher temperature.

The threshold of the response to temperature differences shown by the two species of fish at Bournedale (0.5° C.) agrees very closely with that reported by Shelford and Powers (1915) for herring fry. This threshold may seem high compared to the minimum effective thermal stimulus range for certain fresh-water fishes (differences of 0.03° to 0.07° C.) reported by Bull (1936). However, it must be remembered that this temperature difference represents the minimum temperature difference which will provoke an unconditioned orientative response in the fish. The minimum temperature difference which can be perceived by the fish is probably much less.

Powers and Hickman (1928) presented evidence to show that rivers draining lakes usually had lower CO_2 tensions than other rivers (average difference 0.5 mm. Hg). Powers (1939) contended that by means of these differences in CO_2 tension migrating fish could select certain types of streams. The results of the CO_2 experiments at Bournedale would fit well into his argument. The alewife and the glut herring both showed a strong preference for water of lower CO_2 tension (threshold difference 0.1 mm. Hg). These fishes usually spawn in small ponds and shallow lakes and the choice of water of lower CO_2 content would result in the selection of streams leading to lakes or ponds.

The fundamental nature of the response of the fish to differences in CO_2 and to differences in temperature is indicated by the manner in which CO_2 and temperature were able to dominate competing orienting factors in the exploratory tests shown on page 390. The low threshold values for these responses also suggest their probable importance.

The experiments examining the orientative influence of *p*H (p. 388) confirm the conclusion of Powers (1930) that *p*H was largely ineffective as a factor influencing the behavior of aquatic animals. Whether the response of the fish in the experiments at Bournedale was to differences in free CO_2 or to the associated differences in HCO_3 was not actually established although the threshold values involved suggest that the response was to free CO_2. If the response was to the free CO_2 the influence of CO_2 differences is limited to waters with a *p*H of less than 8.4. This fact might be used to advantage in an experiment to determine to which of the two factors the fish are responding.

Although the main efforts of this investigation were directed toward examining the orientative influence of CO_2 and temperature upon the migrating fish, this was not meant to imply that these are the only major influences which might be concerned in other situations. The influence of differences in dissolved O_2 may be of great importance when lower O_2 values are concerned, which was not the case at Bournedale. Under special conditions flow characteristics such as velocity and turbulence may play an important part in directing the fish. The role of olfactory memory needs to be further explored. The influence of factors affecting the orientation of the fish indirectly (e. g., by controlling the depth of swimming) must be considered. It was largely to stress the fact that many factors may be concerned in fish orientation that the exploratory tests involving velocity, turbulence, and visual factors were included in this report.

Perhaps one of the most important considerations to which the foregoing experiments call attention is that not only are there many factors which may have a directional influence upon the migrating fish but also that they must all be considered together. The experiments examining the relative influence of CO_2 and temperature demonstrated conditions under which the response to temperature differences could dominate the response to CO_2 differences when the factors were in opposition. The reverse situation was also demonstrated. The experiments further revealed circumstances under which the two factors were equal and the influence of the one balanced the influence of the other. Had an observer at these experiments been considering only temperature, for example, he would have seen the fish choose the warmer water in one group of tests and the colder water in another. During the third group of tests he would have concluded that the fish were indifferent to temperature. It is quite possible that many apparently contradictory observations may be explained in this way, e.g., the observations of Ward (1920), Chamberlain (1907), and Foerster (1929), regarding the influence of temperature on sockeye salmon.

One of the considerations that had to be taken into account during the experiments at Bournedale was that the fish might be reacting to a change in water conditions. This possibility became evident in one of the exploratory tests examining the influence of light intensities. One channel of the experimental trough was shaded and the other was left exposed to full sunlight. When the undivided lower portion of the experimental trough was shaded, the fish chose the shaded channel. When the lower part of the trough was exposed to sunlight, the fish chose the sunlit channel. Thus the fish showed no preference for either the sunlit or the shaded channel. They simply avoided any change in light conditions.

During experiments in which water was modified by the introduction of gaseous CO_2 the fish avoided the modified water. Although the fish entered the trough in a mixture of water from both channels (fig. 2), and before entering they had been subjected to a mixture of both waters in the upstream end of the retaining pool (fig. 4), the possibility that the reaction of the fish was one to change in chemical conditions still had to be considered. However, in one experiment which was made at Bournedale, the CO_2 content of the water of one channel was reduced by the addition of NaOH. In that experiment (see p. 388) the fish showed a preference for the modified water. It, therefore, seems improbable that the response of the fish in the other CO_2 experiments was a response to change in chemical conditions.

Powers and Clark (1943), discussing certain gradient-tank experiments with brook trout, *Salvelinus f. fontinalis*, and rainbow trout, *Salmo gairdneri iridus*, presented evidence indicating that the reactions of the trout to CO_2 in these experiments might be characterized as reaction to change. They made the observation that "The immediate response to carbon dioxide tension of the water depends to a large extent upon the carbon dioxide tension to which the fish is adjusted." The period of adjustment in their experiments was only 10 to 15 minutes.

If this observation were true for migrating fish then CO_2 would probably have little directive influence. The fish adjusted to the CO_2 tension of the sea would be restrained from entering fresh water with a different CO_2 tension. At a junction between two streams the fish would tend to select the stream with the larger volume in an effort to remain in the CO_2 tension nearest to the one to which it had become adjusted.

A possible explanation is suggested by an earlier statement of Powers (1939):

> The ova and sperm heads contain a protein (protamine) containing large percentages of arginine. It requires a vast protein metabolism to obtain the necessary arginine. Protein metabolism and especially fasting—both necessary for the liberation of arginine from the muscular tissue of the salmon—tends to produce acidosis of the blood, *i. e.*, lower the alkali reserve of the blood. This is common knowledge. A salmon with a low alkali reserve blood would find low carbon dioxide tension water more advantageous.

The special physiological state of the migrating fish might prevent it from becoming adjusted to its environment.

As experimental evidence is acquired indicating physical and chemical differences may have a directional influence upon migrating fish, the method by which the fish is oriented to these differences becomes an important consideration, particularly when one is trying to relate artificial experimental conditions to situations found in nature.

There are two methods by which fish might become oriented in a gradient. The fish might make a simultaneous comparison of intensities of stimulation by means of symmetrically placed receptors and turn toward (or away from) the maximum stimulation. If this was the method of orientation, the orientative influence of gradients would be limited to those gradients great enough so that the differences between points a few inches apart (the distance between paired receptors) are above the threshold of sensory perception of fish. Gradients as high as this do actually exist in nature but usually only as a narrow zone between two bodies of water which are just beginning to mix.

A second method by which a fish might orient in a gradient is similar to the "trial" method of orientation characterized by Jennings (1906) as "selection from among the conditions produced by various movements." He points out that in this type of behavior, "Each stimulus causes as a rule not merely a single definite action that may be called a reflex, but a series of "trial" movements, of the most diverse character, and including at times practically all the movements of which the animal is capable." This type of orientation Fraenkel and Gunn (1940) have labeled "klinotaxis," and defined as "a directed orientation made possible by means of regular deviations and involving comparison of intensities at successive points in time," and they pointed out examples of such behavior in many invertebrates. In this method of orientation the fish, subjecting itself to varied conditions by its active movements, would select the most favorable condition or direction. The method involves both movement and comparison of intensities of stimulation that are successive in time.

The behavior of the fish as they selected a channel in the experimental trough at Bournedale strongly suggested that this latter method of orientation is the one used. As the fish entered the trough they usually swam from one side to the other, approaching first one channel and then the other. When once the fish had left the narrow zone in which the water was mixing (fig. 2) it was no longer subjected to a gradient. Its sensory receptors were all subjected to the same intensity of stimulation and, therefore, the current was the only orientative influence directing the movement of the fish upstream, unless memory was involved. Yet the fish repeatedly swam from one side of the trough to the other and frequently even after entering one channel, they turned back and entered the other.

Orientation by means of a comparison of intensities that are successive in time would make it possible for fish to become oriented in much smaller gradients than would be necessary if orientation was by a simultaneous comparison of intensities. The minimum gradient in which a fish could orient would depend on the speed of the fish and the time interval of its sensory memory.

The experiments at Bournedale have demonstrated that one group of migrating anadromous fishes will orient with reference to differences in certain physical and chemical water characteristics created artificially. It is logical to suppose that the fish will also be oriented by similar differences occurring along their migration routes in nature.

SUMMARY

The purpose of this investigation was to examine experimentally the influence of certain physical and chemical water characteristics upon the orientation of one type of migrating anadromous fish. The migrating fish were presented with a choice between two channels that carried water with different characteristics. The orientative influence of the water properties in question was measured by the number of fish selecting each channel. The reactions of more than 8,000 fish of the genus *Pomolobus*—alewife, *P. pseudoharengus* (Wilson), and glut herring, *P. aestivalis* (Mitchill)—were tested as the fish migrated upstream through the Herring River at Bournedale, Mass., toward their spawning area, in the springs of 1949 and 1950.

The fish were not removed from the stream or handled in any way. Each was tested individually and tested only once (the few exceptions are noted). The findings of this investigation were:

1. Presented with a choice of waters having different temperatures, 77 percent of the fish entered the channel with the warmer water when the temperature difference continuously exceeded 0.5° C. The temperature differences examined ranged from 0.4° to 3.0° C. Water temperatures during experiments varied from 11.1° to 22.3° C.

2. The response of the fish to temperature differences near the threshold difference decreased as the temperature level of the water increased.

3. Presented with a choice of waters having different amounts of free CO_2, 72 percent of the fish entered the channel with water of a lower

free CO_2 content when the free CO_2 difference exceeded 0.3 p. p. m. (0.1 mm. of Hg in terms of CO_2 tension). The differences in free CO_2 examined ranged from 0.2 p. p. m. CO_2 to greater than 4.0 p. p. m. The amount of free CO_2 in the water during these experiments varied from 0.8 p. p. m. to 7.1 p. p. m.

4. The sex of the fish appeared to have no influence on its response to differences in CO_2 content or in temperature.

5. Exploratory experiments indicated that visual factors and such factors as velocity and turbulence can influence orientation.

6. The fish did not respond to a difference of 1.1 p. m. m. O_2 created during experiments. The amount of O_2 in the water during the experiments ranged from 10.5 p. p. m. to 10.7 p. p. m. and water temperatures ranged from 15.4° to 19.1° C.

7. The fish were indifferent to *p*H differences as large as 0.8 *p*H unit when associated differences in free CO_2 were less than the threshold 0.3 p. p. m. The *p*H of the water varied from 6.5 to 7.3 during these experiments.

8. The relative orientative influence of CO_2 and temperature, when the two factors were in opposition, was shown to depend upon their relative differences of magnitude. A difference in temperature of approximately 2° C. dominated an opposing difference in free CO_2 of 2.0 p. p. m. A difference of CO_2 slightly in excess of 2.4 p. p. m. balanced the opposite effect of a 2° C. temperature difference. A difference of >7.0 p. p. m. CO_2 dominated over a temperature difference of 0.6° C.

9. The behavior of the fish during the experiments indicated that the orientation was accomplished by a method of "trial" involving both movement of the fish and a comparison of intensities of stimulations which were successive in time.

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ABSTRACT

The influence of certain physical and chemical characteristics of water upon the orientation of one type of anadromous fish was examined by presenting the migrating fish with a choice between two channels with different water characteristics. The orientative influence of the water properties was measured by the number of fish selecting each channel. The reactions of more than 8,000 fish of the genus *Pomolobus*—alewife, *P. pseudoharengus* (Wilson), and glut herring, *P. aestivalis* (Mitchill)—were tested as the fish migrated upstream through the Herring River at Bournedale, Mass., toward their spawning area.

Presented with a choice of waters having different temperatures, 77 percent of the fish entered the channel with the warmer water when the temperature difference continuously exceeded 0.5° C. The response of the fish to temperature differences near the threshold difference decreased as the temperature level of the water increased. Presented with a choice of waters having different amounts of free CO_2, 72 percent of the fish entered the channel with the water having the lower CO_2 content when the free CO_2 difference exceeded 0.3 p. p. m. The sex of the fish appeared to have no influence on its response to differences in CO_2 or temperature. Experiments indicated that velocity and turbulence can influence orientation. The relative orientative influence of CO_2 and temperature, when the two factors were in opposition, was shown to depend on their relative differences of magnitude.

Behavior of the fish during the experiments indicated that the orientation was accomplished by a method of "trial" involving both movement of the fish and a comparison of intensities of stimulations which were successive in time.

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No. 8. FORAMINIFERA ECOLOGY OFF PORTSMOUTH, NEW HAMPSHIRE

By Fred B Phleger

AND

No. 9. FORAMINIFERA SPECIES OFF PORTSMOUTH, NEW HAMPSHIRE

By Frances L. Parker

With Six Plates

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No 8 — *Foraminifera Ecology Off Portsmouth, New Hampshire*[1]

By Fred B Phleger

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INTRODUCTION

The marine area covered in this study is in the western Gulf of Maine off coastal northern Massachusetts, New Hampshire, and southern Maine. It extends from Ipswich Bay and Cape Ann on the south to a few miles north of Portsmouth, New Hampshire, on the north, a straight line distance of about 28 miles. Samples were taken from nearshore to approximately 30 miles offshore in the north and to 18 miles offshore in the south, covering an area of about 600 square miles.

The eastern, seaward limit is at Jeffreys Ledge, a relatively shoal area covered with sand and stones of glacial origin. Shoreward from Jeffreys Ledge is a rather elongate basin trending north-northeast which is open at the northern end but closed at the south by the convergence of Jeffreys Ledge and Cape Ann. This will be called the "Portsmouth basin" in this report. There are steep slopes on the sides of the Portsmouth basin and it is constricted near the southern end by submerged ridges extending from Jeffreys Ledge and the Isles of Shoals. Landward from the Portsmouth basin in the northern section there is a submerged topography similar to the glacial topography found on the nearby land. This northwest section has a rough topography with many small hills and enclosed basins. The southern part of the nearshore area is a relatively smooth sand plain grading seaward into a mud and sand plain. Maximum depth of water in the area covered is less than 200 meters.

The purpose of this study is to examine some of the effects of the environment on the distribution of shallow-water benthonic Foraminifera and especially the effect of type of sediment. The area was chosen because all the principal nearshore marine sediment types are represented, except coral. Also the distribution of temperature and salinity is moderately well known in the area.

Most of the bottom samples were collected by David B. Erikson and George Kellogg during the summer of 1946, using the facilities of the Woods Hole Oceanographic Institution. Laboratory analysis of many of the samples was done by Jean F. Peirson. Field work was supported by Office of Naval Research Contract No. N6onr-277, and laboratory work by Contract N6onr-277, Task Order III, with the Woods Hole Oceanographic Institution.

METHOD OF STUDY

Field Work

Stations for bottom samples are located in a series of traverses which form a closely spaced grid pattern. Stations are spaced ½ to 1 mile apart on each traverse and traverses are 1 to 2 miles apart; a total of 738 samples was collected. The geographic position of each sample used in this paper is given in Table 1

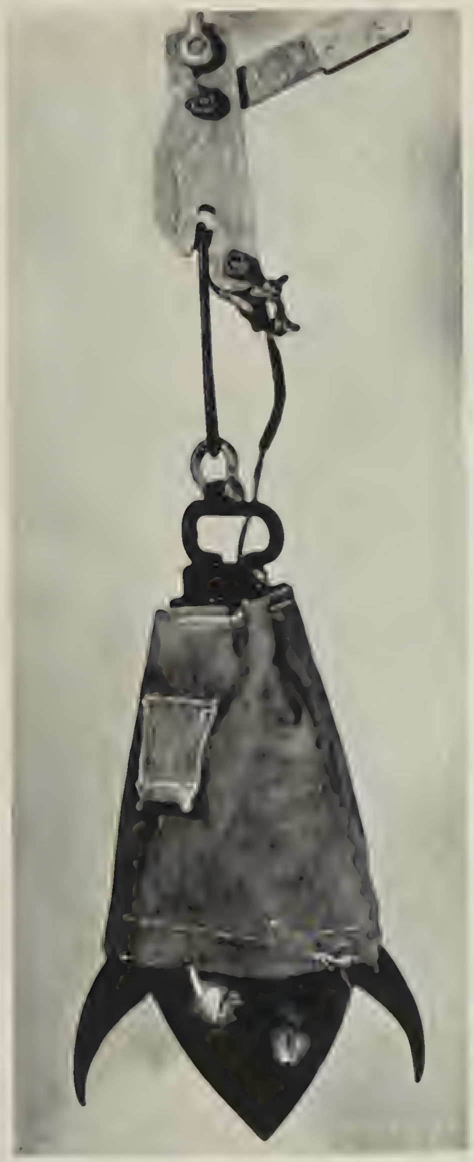

Figure 1. Orange-peel dredge

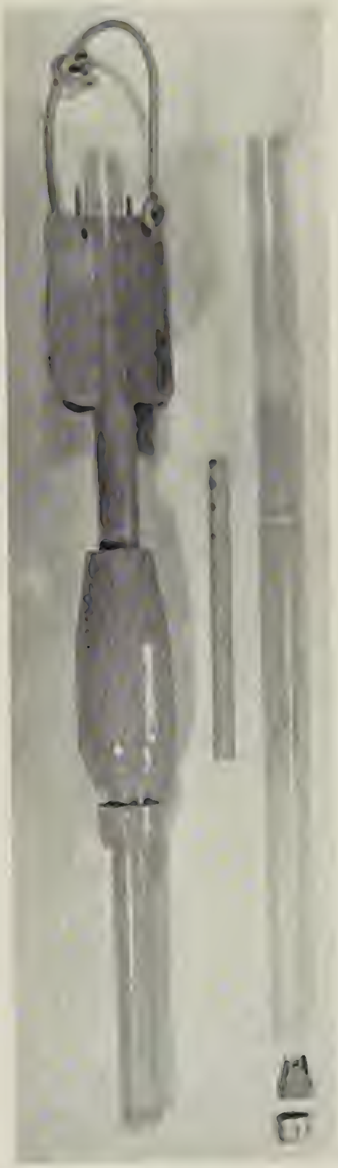

Figure 2. Short coring tube

A small orange-peel dredge (Figure 1) was used where the bottom sediments contained pebbles larger than about 1 inch in diameter. This dredge has a rated capacity of 100 cubic inches and obtains a large sample. It is fitted with a canvas hood to prevent washing of the sample enroute to the surface. The hood is attached to the upper edge of the jaws of the dredge by brass cotter pins through small holes drilled in the dredge. The upper surface of the hood is tied with a heavy draw string. Two water ports are cut in the hood to aid circulation of water through the dredge as it is lowered; these are covered with weighted canvas flaps to prevent undue water circulation and agitation of the sediment as the sampler is brought to the surface. A tripping device enables the dredge to be used from a single wire, as shown in Figure 1. This is hooked to a long, single link and the wire rope which operates the drum closing the dredge jaws is attached to the frame of the tripping device. The hook remains in the link while

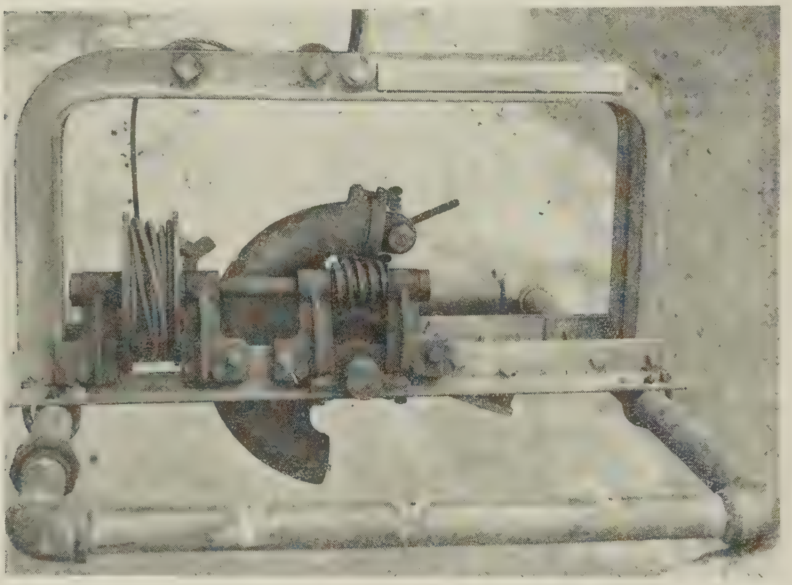

Figure 3. Stetson-Iselin sampler. The curved brass tube is forced into the sediment by action of the worm gear as the wire is hauled off the drum. Washing of the sample is prevented by sealing the open end of the tube against a rubber pad and closing the valve at the opposite end on the last turn. The sediment is extracted by slipping the axle and removing the curved tube from the frame of the sampler.

there is tension on the hoisting cable. When the sampler rests on the bottom and the hoisting wire becomes slack, the hook is disengaged from the link by fall of the weighted arm to which it is attached. As the wire is hoisted, tension is on the wire operating the jaw-closing mechanism and jaws are closed.

The small orange-peel dredge was used with success in this area down to depths of 150 meters or more. It occasionally falls on its side on the bottom but this generally can be avoided by lowering it slowly. There is some washing of the surface of the sediment sample after the dredge is taken from the water but this can be minimized by letting the water drain off the sediment with the jaws closed. A representative sample was taken from the surface of the sediment obtained. Small boulders occasionally were obtained with the orange-peel dredge.

The Stetson-Iselin sampler (Stetson, 1938) was used in areas of clean sand (Figure 3). The sample taken with this instrument is in a curved brass tube 2 inches in diameter. The sample is sealed into the brass tube and cannot be washed enroute to the surface. It is believed that this gear obtains a more representative sample of sand than any other yet in operation. It should not be used where there are pebbles approaching the diameter of the brass tube.

The Phleger sampler (Figure 2) was used in sediment consisting of mud or mud and sand. This is a small coring device consisting of a steel tube provided with a lead weight and tail fins. The steel tube contains a thin plastic liner of 1⅜ inches inner diameter in which the sediment is caught as the sampler plunges into the bottom. A spring-brass core-catcher aids in preventing loss of the core as the tube is extracted from the bottom and hauled in. Cores usually are up to 40 cm. long and each sample is retained in the plastic tube which serves as its permanent container. This gear obtains a relatively undisturbed sample of the surface sediment together with the sea water from directly above the bottom. Neutral formaldehyde was placed in the water in the plastic tube to make approximately a 5 per cent concentration; the purpose of this is to preserve the living Foraminifera fauna.

Laboratory Analysis

The total population of Foraminifera was determined in 318 samples of the surface of the bottom sediment. The living population of Foraminifera in the upper centimeter of sediment was determined in 213 of these samples. The vertical distribution of faunas was determined in 18 of the short cores, and the fauna of the bottom samples was analyzed from 38 of the short cores. All samples chosen for study of Foraminifera are so distributed that a representative survey is obtained of the whole area.

Faunas studied from the top of the short cores consisted of the upper centimeter of sediment. This material had been preserved in a solution of sea water and formaldehyde. The sediment was washed over a brass sieve having openings of .074 mm. The washed material was placed in a petri dish with additional tap water. The presence of specimens which contained protoplasm, and hence were presumed to be alive at the time the samples were collected, was determined by the use of Millon's reagent. Millon's reagent is made by dissolving one part by weight of mercury in two parts of concentrated nitric acid and diluting with twice its volume of water. The precipitate which forms is allowed to settle to the bottom and the supernatant liquid is used. A few drops of this reagent added to a solution and heated will cause protein to be colored bright red.

Millon's reagent contains free nitric acid and thus cannot be used on a sample containing calcareous Foraminifera. Samples examined for living specimens were almost exclusively composed of arenaceous species which are not affected by acid. Each sample was examined for calcareous Foraminifera before adding the reagent and the specimens discovered were recorded. There were only occasional calcareous specimens in a few samples. Several drops of Millon's reagent were added to the solution and the sample was warmed for 4 to 6 hours by the heat of a 75 watt incandescent lamp in a desk stand. It was generally desirable to break each arenaceous specimen to determine whether the presence of protoplasm was indicated by the characteristic red color. The number of specimens and the living population of each species were recorded. These are converted into percentage of the total living population for purposes of tabulation.

The amount of sediment collected by the Stetson-Iselin sampler and by the orange-peel dredge was rather large. An attempt was made to select an amount of material from each of these samples approximately equal to the amount taken from the surface of the undisturbed short cores.

The vertical distribution of Foraminifera in the short cores was determined from adjacent samples comprising a half section of the core. Each core sample was approximately 3 to 5 cm. long, except where a change in appearance of the sediment made more frequent sampling appear desirable. Each sample was trimmed on all sides to avoid contamination from adjacent parts of the core.

Distribution of each of the more abundant species in the area is plotted in Figures 7 to 25. The distribution is indicated in these figures in percentage groups as follows: less than 1, 1 to 5, 5 to 15, 15 to 25, 25 to 50, and more than 50 per cent. The actual percentage of all species in each sample is listed in Tables 2 to 7. Descriptions and illustrations of the species are in the accompanying paper by Parker.

SEDIMENT DISTRIBUTION

A brief description of the distribution of principal areas of the sediments is included here because of the apparent relationship with the distribution of many Foraminifera species. A generalized chart of sediment distribution is shown in Figure 4. This chart is based upon sediment mechanical analyses made principally by David B. Erikson and is published here in preliminary form. It is anticipated that a more comprehensive analysis of sediment distribution in the area will be contained in a future report.

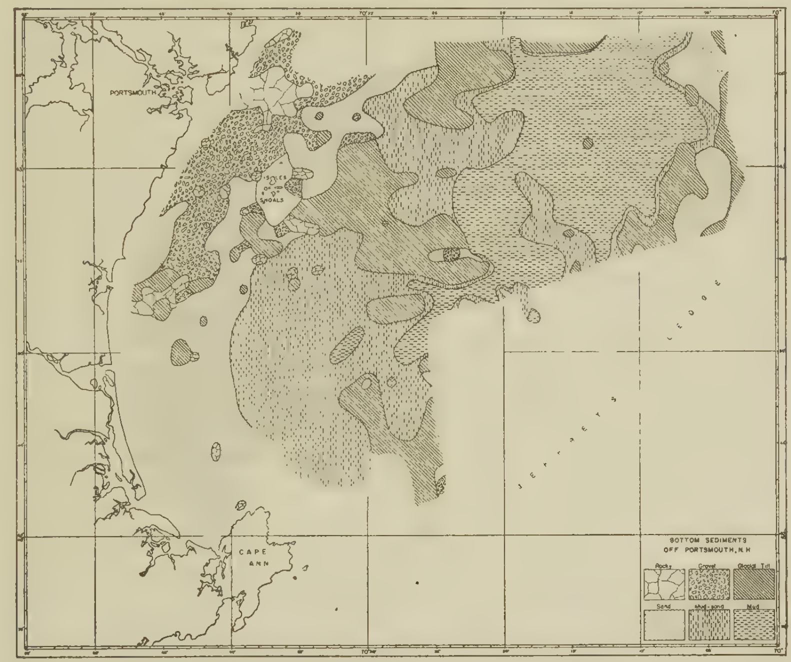
PORTSMOUTH
ISLES OF SHOALS
CAPE ANN
BOTTOM SEDIMENTS
OFF PORTSMOUTH, N.H.
Rocky
Gravel
Glacial Till
Sand
Mud-sand
Mud
70°

Figure 4. Distribution of sediments

The nearshore zone from Cape Ann to north of the Merrimack River contains clean, well-sorted sand. In the north there is a large area of gravel or stony bottom, with some patches of rock, grading seaward into sand. There are two principal mud and sand areas in the central part of the area below depths of about 150 feet. These mud and sand areas are separated by an area of glacial till extending in a northwest-southeast direction. The sediment in the Portsmouth basin is a fine-grained mud. The part of Jeffreys Ledge investigated has two distinct sand areas surrounded by glacial till and mud and sand patches. There are several additional patches of glacial till at various places. Additional information about sediment distribution can be obtained from Figure 4.

DISTRIBUTION OF TEMPERATURE AND SALINITY

The temperature distribution in the Portsmouth area is relatively uniform for the area as a whole, although there are small local variations. The large seasonal variations are approximately similar throughout the area, so that the geographic temperature distribution is quite uniform. The vertical temperature structure at any one place gives a good picture of the structure at all other places of equal water depth. This area has water temperatures which are similar to those of the rest of the Gulf of Maine. They are thus significantly lower than the temperatures of coastal waters south of Cape Cod, especially during the summer and early autumn. There is no apparent effect from the warm waters of the Gulf Stream system due principally to topographic barriers, and also probably due to the presence of colder northern water masses. Most of the summer heat of the Gulf of Maine probably is produced by solar warming *in situ* and is of local origin according to Bigelow (1924, p. 699).

Salinity distribution in the Portsmouth area also is relatively uniform except for a slight decrease in salinity shoreward and in the Portsmouth basin where there is somewhat more saline bottom water than upper water. In the nearshore area effluents of less saline surface water occur off the mouths of the Merrimack and Piscataqua Rivers during times of flood, usually during the spring season and occasionally in the autumn season. This surface water of low salinity is mixed with the lower, more saline water during times of strong wind and may produce somewhat less saline water at the bottom in the shoal coastal areas. There is a coastal current flowing in a southerly direction according to Bigelow (1924, p. 974). This may tend to accumulate surface waters of low salinity, having their origin from the Merrimack River, between the Merrimack and Cape Ann.

Temperature and salinity data used are from the files of the Woods Hole Oceanographic Institution and were furnished by D. F. Bumpus. Many of the data were collected by C. R. Hayes and W. G. Metcalf. The following is a brief summary of the seasonal temperature and salinity distribution given in terms of mean monthly conditions. Mean monthly temperatures are generalizations which tend to obscure daily and other irregularities; actual extreme temperature ranges, for example, are always larger than mean monthly temperatures indicate.

Minimum surface temperatures occur during February when the monthly mean varies from a minimum of about 2° C. near the shore to 4° C. offshore. The water is essentially isothermal to the bottom even in the deepest part of the Portsmouth basin. These temperatures persist through March, there is a little surface warming during April, and by May the surface temperatures have reached approximately 8 to 9° C. A surface thermocline has developed in the upper 30 or 40 m. and the bottom temperatures average about 4.5°C., except in very shoal nearshore areas. Maximum surface temperatures are reached by August, when they average about 15.5 to 17°C. There is a strong thermocline in the upper 40 to 50 m. of water and bottom temperatures in the deepest part of the area are about 5.5° C. Essentially this condition obtains through September, marked cooling occurs during October, and by November the surface temperatures are 9 to 10° C. with either a very weak thermocline developed or essentially isothermal water to the bottom of the deepest part of the area. There is then progressive cooling and mixing at least through February.

Salinities during the winter months are rather uniform in geographic and bathymetric distribution at $32^{0}/_{00}$ to $32.5^{0}/_{00}$. By April the nearshore surface salinities are reduced to about $30^{0}/_{00}$, the offshore surface water is about $32^{0}/_{00}$ and there is a slight increase of salinity with depth to a maximum of $32.5^{0}/_{00}$ at the bottom of the Portsmouth basin. During the late spring and early summer minimum surface salinities of about $29^{0}/_{00}$ are reached in the southwest nearshore area between Cape Ann and the Merrimack River. There is a gradual increase in surface salinity until a nearshore average minimum of about $31.5^{0}/_{00}$ is reached in October with the deeper bottom water remaining at about $32.5^{0}/_{00}$. By November the water is essentially isohaline to the bottom at $32^{0}/_{00}$ to $32.5^{0}/_{00}$. Bottom water salinities of $33^{0}/_{00}$ have been recorded from the Portsmouth basin during December.

DISTRIBUTION OF MODERN FORAMINIFERA

Species Distribution

The modern distribution of each species found in the Portsmouth area is summarized in this section. In this area there is a close correlation between the distribution of most of the species and the type of sediment on which it is found. Distribution of the species is described in terms of the areas of different sediment type, as shown on Figure 5; this is a matter of convenience only and is not intended to imply an ecologic interpretation. Species are listed in alphabetical order. For further information consult Figures 7 to 25 and Tables 2 to 7.

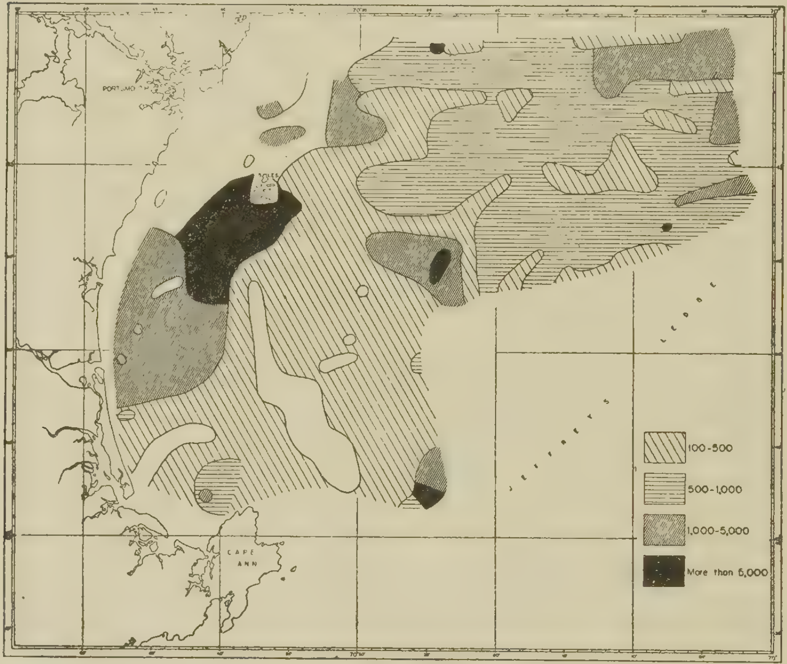

Figure 5. Distribution of total population of Foraminifera in actual numbers of specimens per uniform size sample

BENTHONIC FAUNA

Ammobaculites cassis (Parker) occurs at 12 widely separated stations in frequencies of 1 per cent or less. It is present on most sediment types.

Ammodiscus is present in low frequency in most of the samples from the area. It is always less than 5 per cent of the fauna, and usually less than 1 per cent.

Angulogerina angulosa (Williamson) is present at only a few stations in sand areas. Almost all the occurrences are less than 1 per cent and none are greater than 2 per cent.

Astrononion stellatum Cushman and Edwards is confined to a few stations on sand bottom and has a usual frequency of less than 1 per cent and always less than 5 per cent.

Bolivina pseudoplicata Heron-Allen and Earland is present at 10 nearshore sand stations with an average frequency of less than 1 per cent.

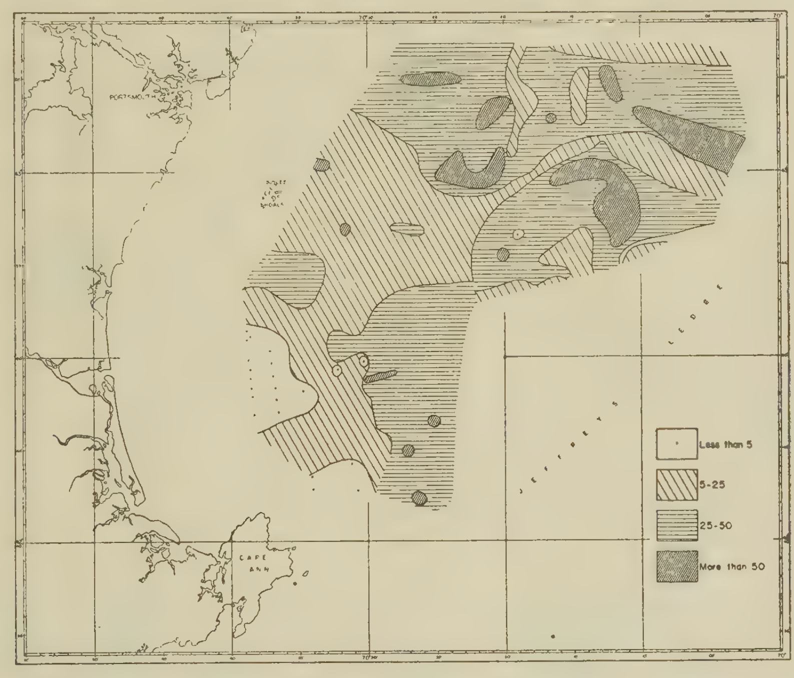

Figure 6. Distribution of living population of Foraminifera in number of specimens per uniform area

Bolivina pseudopunctata Höglund is found at 2 nearshore stations and at 2 stations on a small sand patch in the south-central part of the area. It is less than 1 per cent of the fauna at these stations.

Bolivina subaenariensis Cushman is 0.2 per cent of the fauna at a station in the southeast offshore sand area.

Bulimina aculeata d'Orbigny occurs at 9 widely separated stations on various sand areas with a maximum frequency of 2 per cent.

Buliminella elegantissima (d'Orbigny) is present in 6 widely separated samples from nearshore sand areas at less than 1 per cent of the fauna.

Cassidulina algida Cushman is characteristic of the sand areas and occurs on some of the mud-sand bordering the two eastern sand areas. It reaches its highest frequency in the northeastern section where it occurs as 79 per cent of the fauna at Station 271 and 70 per cent at Station 645.

Cassidulina norcrossi Cushman is less than 1 per cent at 3 stations in the south-central part of the area and is 12 per cent of the fauna at Station 355 and 7 per cent at Station 50.

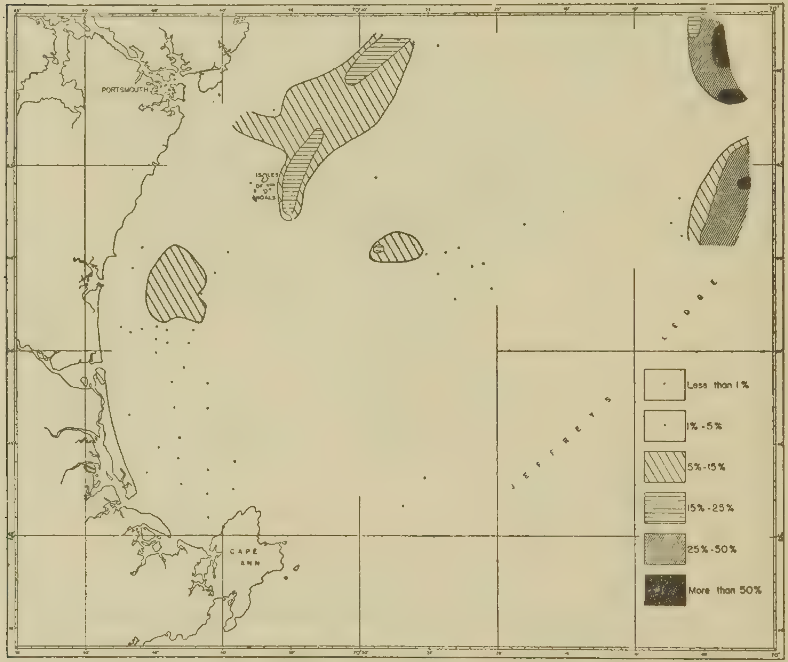

Figure 7. Distribution of *Cassidulina algida* Cushman in per cent of total population of benthonic Foraminifera

Cibicides lobatulus (Walker and Jacob) is characteristic of the sand areas. It reaches its highest percentage north of the Isles of Shoals, where it constitutes 50 to 90 per cent of the fauna, and off Hampton Beach (up to 85 per cent). It is not present in the mud and mud-sand areas.

Crithionina pisum Göes var. *hispida* Flint is present in very low frequency at 4 stations in the Portsmouth basin and at 1 station in the southwest mud-sand area.

Discorbis columbiensis Cushman is found at 18 stations mostly from the southwest, inshore sand area and principally off Hampton Beach. One occurrence is from the northeast sand area and one is from a glacial till patch in the central part of the area. It is usually 1 per cent or less of the fauna but at 2 stations it is more than 5 per cent.

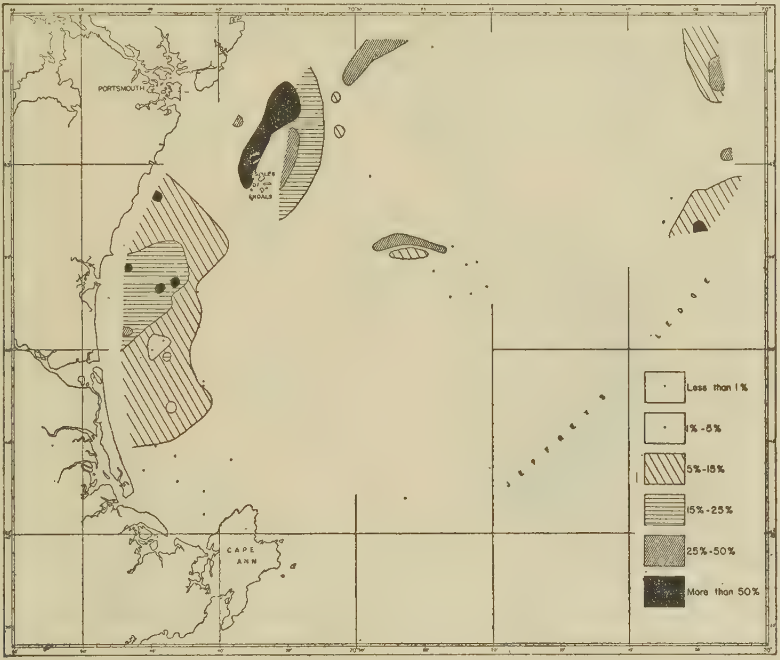

Figure 8. Distribution of *Cibicides lobatulus* (Walker and Jacob) in per cent of total population of benthonic Foraminifera

Discorbis squamata Parker is known from 4 stations on the inshore sand area off the Merrimack River and from 1 station off the Piscataqua River. The frequency varies up to 2 or 3 per cent.

Eggerella advena (Cushman) has its greatest abundance in the southwest sand area where in the southern part of this area the species averages more than 50 per cent of the fauna. There is a regular increase shoreward from the boundary between the mud-sand and the sand. There are two other patches of relatively high frequency, on the seaward side of the Isles of Shoals and in the small northwest sand area. This species occurs at numerous other stations throughout the Portsmouth area but usually is less than 1 per cent of the fauna.

Elphidium articulatum (d'Orbigny) is present in low frequency, usually less than 5 per cent, on the inshore sand and gravel areas and at a few stations on offshore sand areas. At Station 395 it is 14 per cent of the fauna.

Elphidium incertum (Williamson) var. *clavatum* Cushman is characteristic of inshore sand areas and does not occur on mud or mud-sand bottom. Its highest percentage appears to be at water depths less than about 30 meters. It is 48 per cent of the fauna at Station 406 off Plum Island and 31 per cent at Station 554 off Portsmouth.

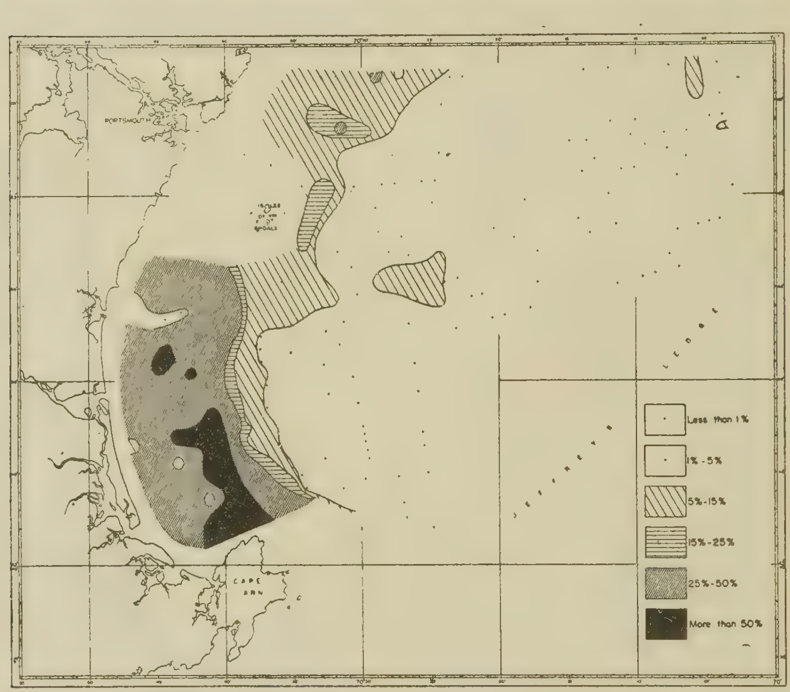

Figure 9. Distribution of *Eggerella advena* (Cushman) in per cent of total population of benthonic Foraminifera

Elphidium subarcticum Cushman is characteristic of the shoal water sand areas. It reaches the highest percentage in the southwest sand area where in the southern section it is 33 per cent of the fauna at Station 376. It does not occur on mud and mud-sand areas.

Eponides frigidus (Cushman) appears to be largely confined to the sand areas. The greatest frequency occurs in a rather large patch east and north of the mouth of the Merrimack River where it averages 8 to 10 per cent of the fauna. It also occurs in the northwest, the south-central, and the two eastern sand areas.

Eponides umbonatus (Reuss) constitutes 0.1 per cent of the fauna at Station 395.

Eponides wrightii (H. B. Brady) is less than 1 per cent of the fauna at one station in the north-central part of the area.

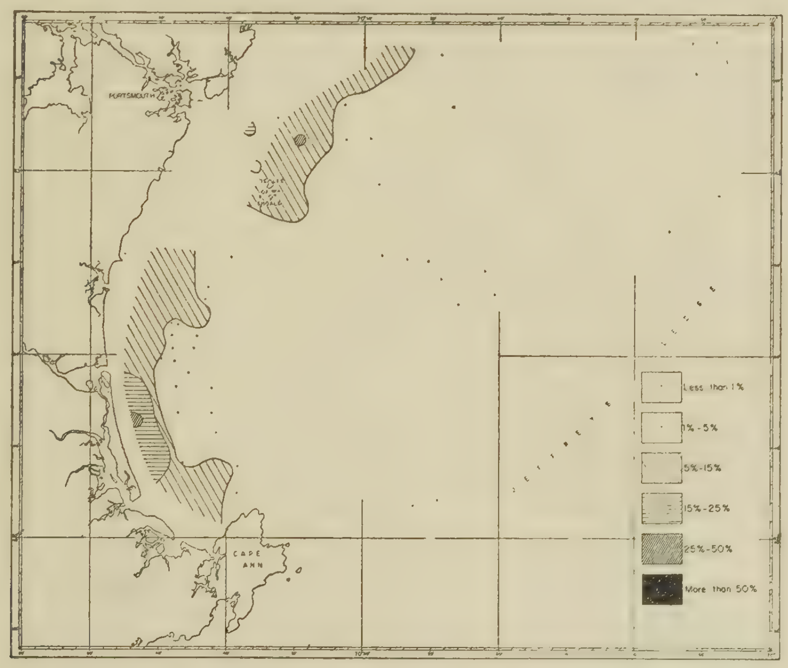

Figure 10. Distribution of *Elphidium incertum* (Williamson) var. *clavatum* Cushman in per cent of total population of benthonic Foraminifera

Globobulimina (*Desinobulimina*) *auriculata* (Bailey) is present at only a few stations and generally constitutes less than 1 per cent of the fauna except in the small sand patch in the south-central part of the area where the species attains a local maximum of 16 per cent.

Glomospira gordialis (Jones and Parker) occurs at numerous stations at frequencies usually less than 1 per cent and not greater than 2 per cent and is present on all types of sediment.

Haplophragmoides bradyi (Robertson) is essentially confined to the mud area in the Portsmouth basin where frequencies as high as 60 per cent occur. The center of greatest abundance is in the north-central part of the basin. It is present at only a few stations outside this area, usually less than 10 per cent of the fauna, and is not present in sand areas. All the living specimens found are from the Portsmouth basin but they occur at only approximately one-half of the stations. There appear to be centers of proliferation of living specimens with no living forms in between the centers.

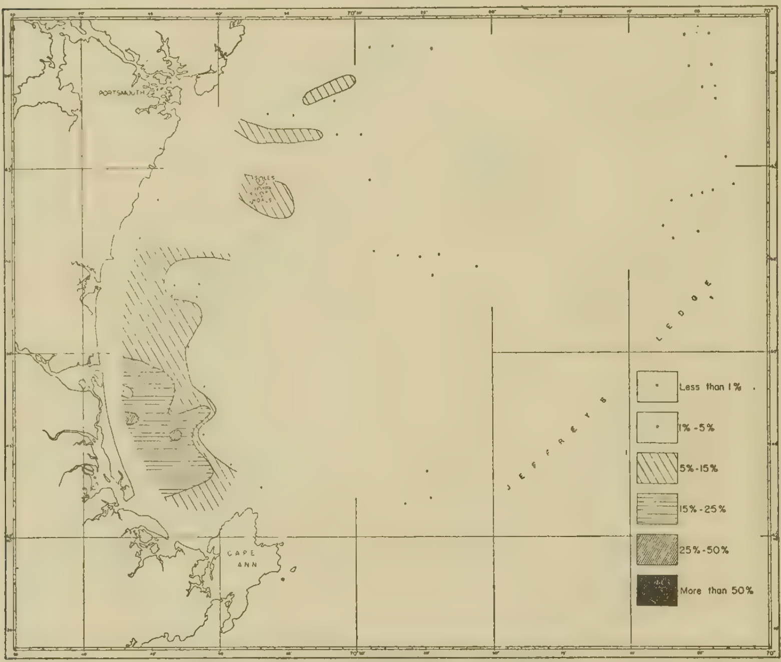

Figure 11. Distribution of *Elphidium subarcticum* Cushman in per cent of total population of benthonic Foraminifera

Haplophragmoides glomeratum (H. B. Brady) is widely distributed with generally high frequency in all parts of the area except on the nearshore sands and gravel and two sand areas on Jeffreys Ledge. Frequencies of more than 30 per cent are common. It occurs in only a few samples from the nearshore materials and usually is less than 1 per cent of the population in these samples.

Hippocrepina indivisa (Parker) is widely distributed at numerous stations, principally in mud and mud-sand areas, with frequencies less than 1 per cent. The greatest number of occurrences is in the southwest mud-sand area.

Hyperammina elongata H. B. Brady is less than 1 per cent of the fauna at numerous stations on all types of sediment except the inshore areas.

Labrospira crassimargo (Norman) is widely distributed in all samples in mud, mud-sand, and central glacial till areas, having an average frequency of 5 to 15 per cent. It also occurs in numerous sand samples but in very low percentage. This species attains its highest frequency in the southwest mud-sand area where it is as high as 80 per cent.

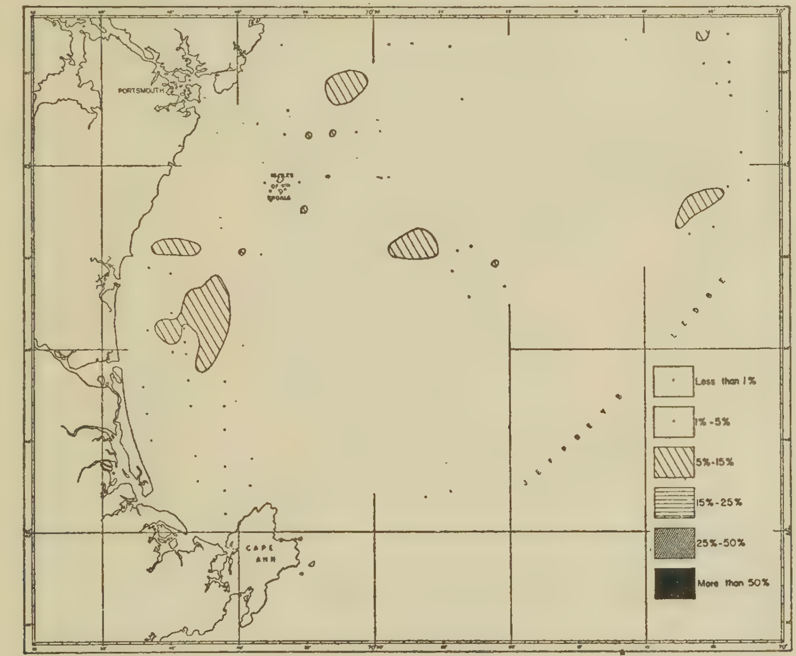

Figure 12. Distribution of *Eponides frigidus* (Cushman) in per cent of total population of benthonic Foraminifera

Labrospira jeffreysii (Williamson) is widely distributed and generally less than 5 per cent of the fauna but has a higher frequency in the mud and mud-sand areas. It does not occur in inshore sand areas. There is an area of high concentration on the eastern end of the mud-sand area and a marked decrease in frequency shoreward from here.

Labrospira cf. *nitida* (Göes) constitutes less than 1 per cent of the fauna at 12 stations in the Portsmouth basin.

Miliammina fusca (H. B. Brady) is found at 7 stations in the nearshore, southwest sand area. All occurrences are from off the mouth of the Merrimack River and southward from there. It is less than 1 per cent at 6 stations and 2 per cent at 1 station.

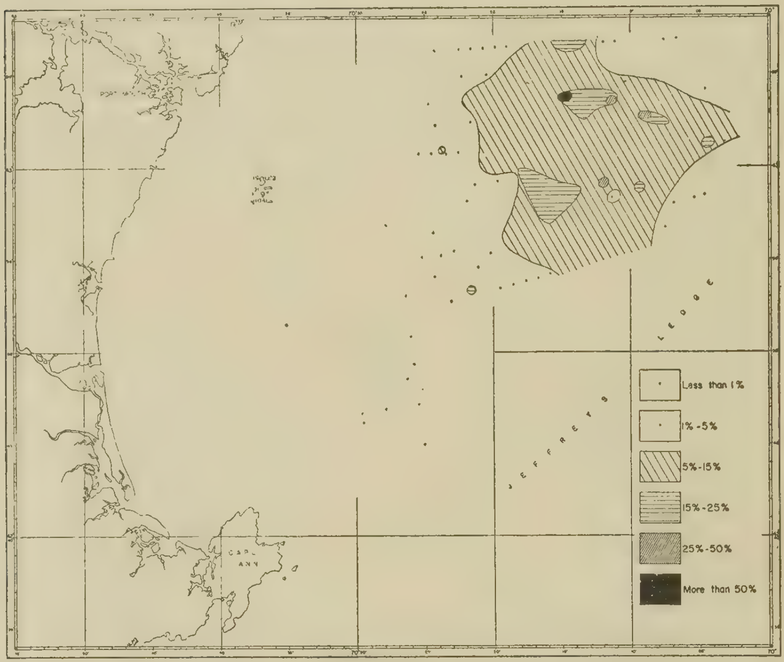

Figure 13. Distribution of *Haplophragmoides bradyi* (Robertson) in per cent of total population of benthonic Foraminifera

Nonion labradoricum (Dawson) is present at only 37 stations and usually with a very low frequency. It occurs at 5 stations in the southwest sand area where it has a frequency of less than 1 per cent, and at a few stations in the northwest sand and gravel areas. The highest frequency is in the glacial till east of the Isles of Shoals and in the small eastern sand areas where locally it has a concentration of 15 per cent or more.

Nonionella auricula Heron-Allen and Earland is present at Station 246 in the central part of the area where it is 0.4 per cent of the fauna.

Patellina corrugata Williamson constitutes less than 1 per cent of the fauna at 7 stations on inshore areas and at 1 station on an offshore sand area.

Proteonina atlantica Cushman is universally distributed throughout the area, constituting a relatively large percentage of almost every sample examined. The lowest frequency is in the north-central mud-sand area, in the inshore part of the southwest sand area, and in the central part of the Portsmouth basin. The distribution of the living population has the same general pattern as the distribution of the empty tests in the samples.

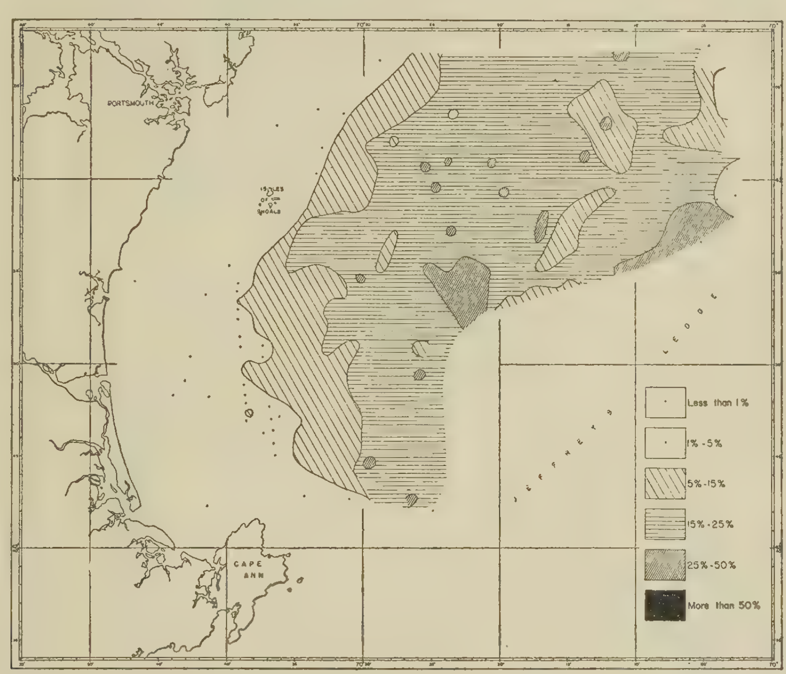

Figure 14. Distribution of *Haplophragmoides glomeratum* (H. B. Brady) in per cent of total population of benthonic Foraminifera

Pseudopolymorphina novangliae (Cushman) has frequencies less than 1 per cent at 9 stations in the inshore sand and gravel areas and at 1 station in the northeast sand patch.

Quinqueloculina arctica Cushman is present at 20 stations in the nearshore sand and gravel at frequencies less than 1 per cent. It was found only north of the mouth of the Merrimack River.

Quinqueloculina frigida Parker was found at 21 stations at frequencies less than 1 per cent, mostly on the nearshore areas. It is present at 5 stations on the southwest mud-sand area.

Quinqueloculina seminula (Linné) occurs at a few nearshore stations with frequencies less than 1 per cent. One occurrence is in the southeast offshore sand area and three occurrences are in the south-central sand patch.

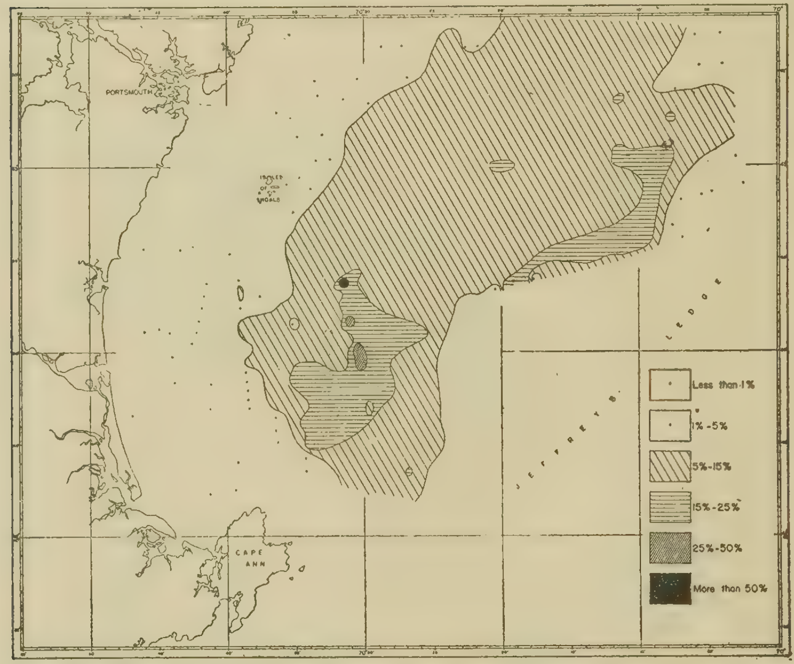

Figure 15. Distribution of *Labrospira crassimargo* (Norman) in per cent of total population of benthonic Foraminifera

Quinqueloculina subrotunda (Montagu) appears to be restricted to the nearshore areas where it is recorded from only a few stations and is usually less than 1 per cent of the fauna. At Station 707 it is 14 per cent of the fauna.

Recurvoides turbinatus (H. B. Brady) has the greatest frequency in the Portsmouth basin where it averages 5 to 15 per cent of the fauna and reaches a maximum of 26 per cent at one station. This species also occurs at most stations in the mud-sand areas, especially in the southwest mud-sand area. It is present at only a few sand stations and is always less than 1 per cent of the fauna where it occurs.

Reophax arctica H. B. Brady is rather widely distributed with the frequency generally less than 5 per cent and in approximately half the samples less than 1 per cent. The greatest concentration is on the inshore side of the southwest mud-sand area where locally it is more than 5 per cent.

Reophax curtus Cushman is a dominant member of the fauna in the mud and mud-sand areas. There are 3 large areas of high concentration, in the north-central mud-sand area and in the southern mud-sand area, and in the Portsmouth basin. In large parts of these areas the species averages more than 30 per cent of the fauna. In sand areas *R. curtus* is usually less than 1 per cent of the fauna at the few stations where it is found.

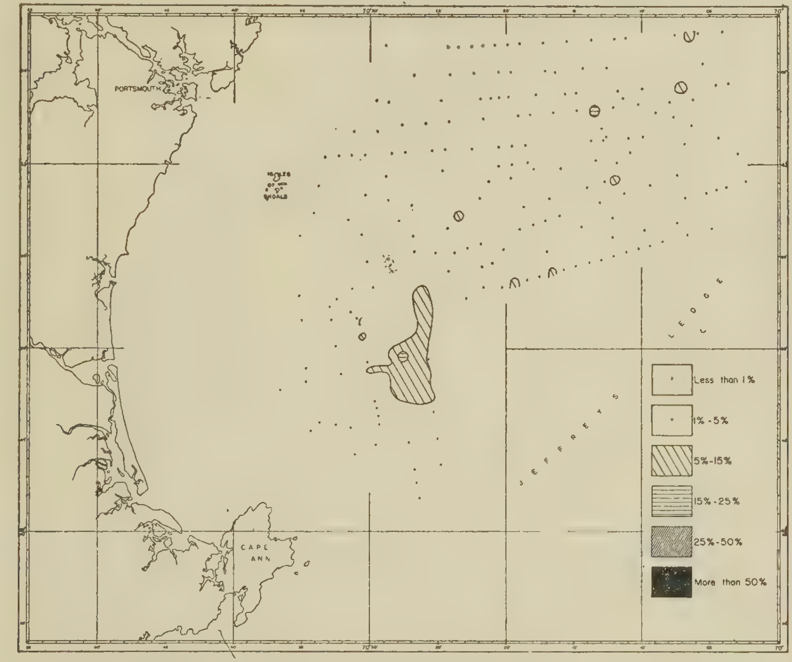

Figure 16. Distribution of *Labrospira jeffreysii* (Williamson) in per cent of total population of benthonic Foraminifera

Reophax scottii Chaster has a very discrete frequency distribution. The highest frequency is on the shoreward side of the southwest mud-sand area where a large patch has an average of 15 to 25 per cent of the species and 1 station has 64 per cent. There is also an area of relatively high frequency in the north-central mud-sand. This species is present at several other places on all types of sediment but in lower percentages.

Spiroplectammina biformis (Parker and Jones) appears to be characteristic of the mud-sand areas. There is a large area of relatively high frequency on the inshore side of the southwest mud-sand. The 5 per cent frequency boundary approximately coincides with the seaward limit of sand. Percentages are generally less on mud than on mud-sand.

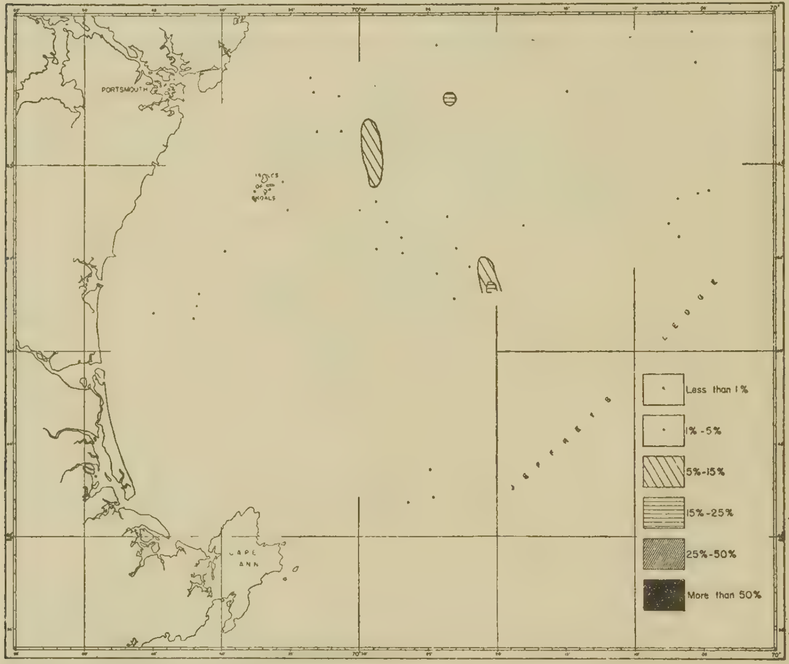

Figure 17. Distribution of *Nonion labradoricum* (Dawson) in per cent of total population of benthonic Foraminifera

Spiroplectammina typica Lacroix is present at numerous stations, widely distributed, and on all types of sediment. The frequency usually is less than 1 per cent but at 1 station it constitutes 4 per cent of the fauna.

Textularia torquata Parker is most abundant on the mud-sand areas and in the central glacial till area where the frequency averages 5–15 per cent or more. The largest area of high frequency (15–25 per cent) is in the southwest mud-sand area. This species is present at most stations in the Portsmouth basin with frequencies less than 5 per cent and also at several inshore sand stations with frequencies of 1 per cent or less.

Triloculina tricarinata d'Orbigny was recorded from one station in each of the following: the southwest sand, the northeast sand, and the southeast sand area. It is 0.2 per cent of the fauna at each station.

Trochammina advena Cushman is present at most stations in the Portsmouth basin with average frequencies less than 1 per cent and none greater than 3 per cent.

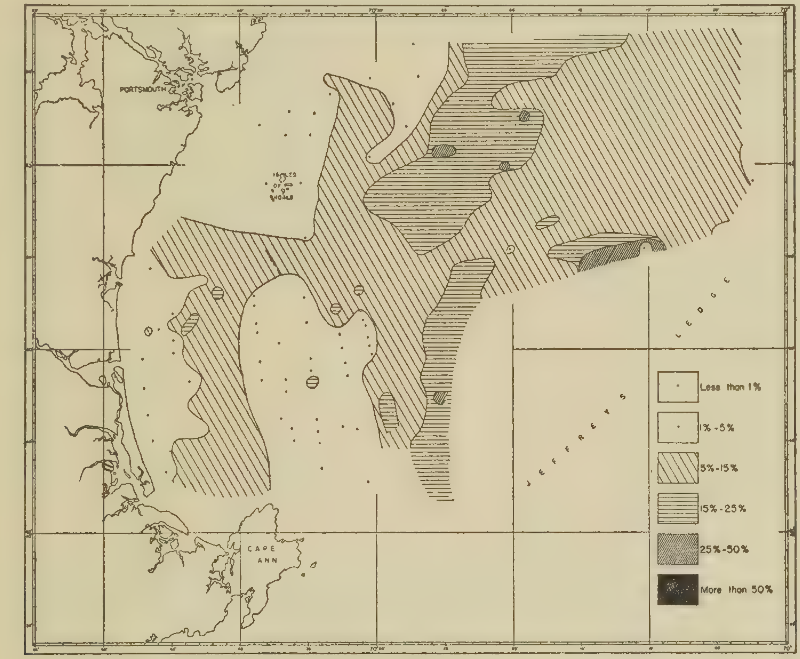

Figure 18. Distribution of *Proteonina atlantica* Cushman in per cent of total population of benthonic Foraminifera

Trochammina inflata (Montagu) is found at 6 stations in the southwest sand area, 5 of which are south of the Merrimack River. One occurrence is off the mouth of the Piscataqua River, and 1 occurrence is recorded from the edge of the Portsmouth basin. Frequencies range up to 4 per cent south of the Merrimack River.

Trochammina lobata Cushman occurs at several of the nearshore sand stations and also at a few of the offshore sand stations, with the greatest number of occurrences in the southwest sand area. Frequencies are up to 5 per cent in the latter area.

Trochammina macrescens H. B. Brady is reported from 1 station off the mouth of the Merrimack River where it is 0.1 per cent of the fauna.

Trochammina quadriloba Höglund was found at numerous stations in the Portsmouth basin where it has a frequency usually less than 1 per cent but as high as 2 per cent. It is essentially restricted to the Portsmouth basin but a few occurrences are recorded from nearby mud-sand areas.

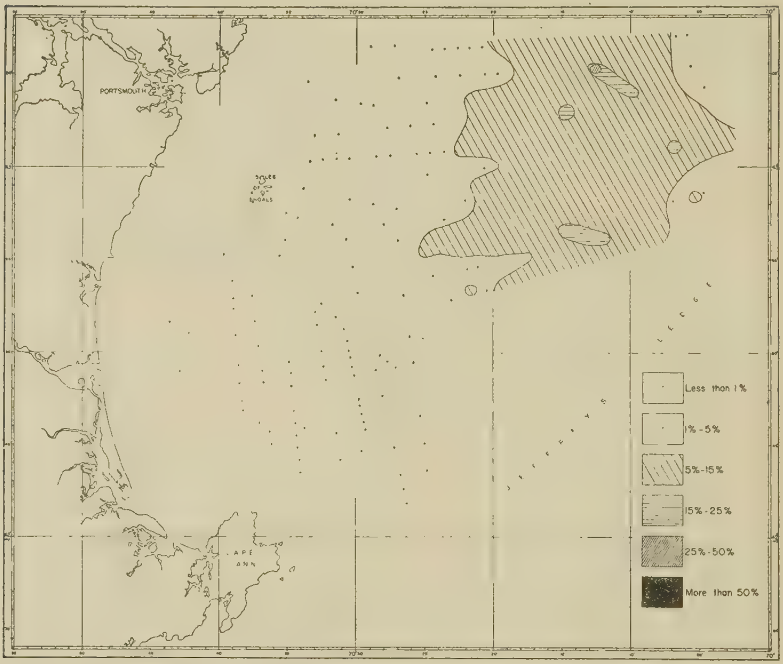

Figure 19. Distribution of *Recurvoides turbinatus* (H. B. Brady) in per cent of total population of benthonic Foraminifera

Trochammina squamata Parker and Jones is widespread on all types of bottom material, occurring at approximately three-fourths of the stations. The highest concentration is on the shoreward part of the southwest mud-sand area, where the shoreward boundary of high frequency approximately follows the boundary between sand and mud-sand. The frequency reaches 35 per cent in this area; elsewhere the frequency is low.

Valvulina conica Parker and Jones was found at several stations mostly in the Portsmouth basin, but at a few stations elsewhere. The frequency is less than 1 per cent where it occurs.

Virgulina complanata Egger is recorded from 11 stations in off shore sand areas where it is 2 per cent or less of the fauna. It has not been discovered at any of the nearshore stations. This species appears to occur in small, but well-defined patches.

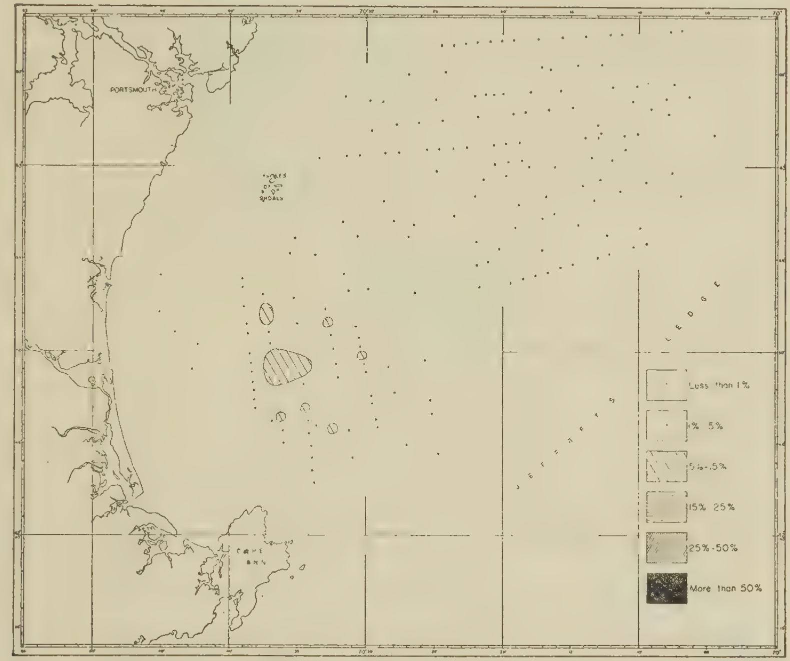

Figure 20. Distribution of *Reophax arctica* H. B. Brady in per cent of total population of benthonic Foraminifera

Virgulina fusiformis (Williamson) occurs at only a few stations with a frequency usually less than 5 per cent. It appears to be confined to sand bottom.

PLANKTONIC FAUNA

Planktonic Foraminifera were discovered in surface sediment samples at the following stations: 23, 50, 197, 224, 246, 356, 372, 404, 610, 614, 647, 685, and 736. Planktonic specimens constitute a very minor element of the fauna at these stations; 120 specimens were found at Station 224, in marked contrast to the abundance at most places. The specimens all belong to *Globigerina bulloides* d'Orbigny and *Globigerina* sp., except for one specimen of *Globigerinoides rubra* (d'Orbigny) at Station 50.

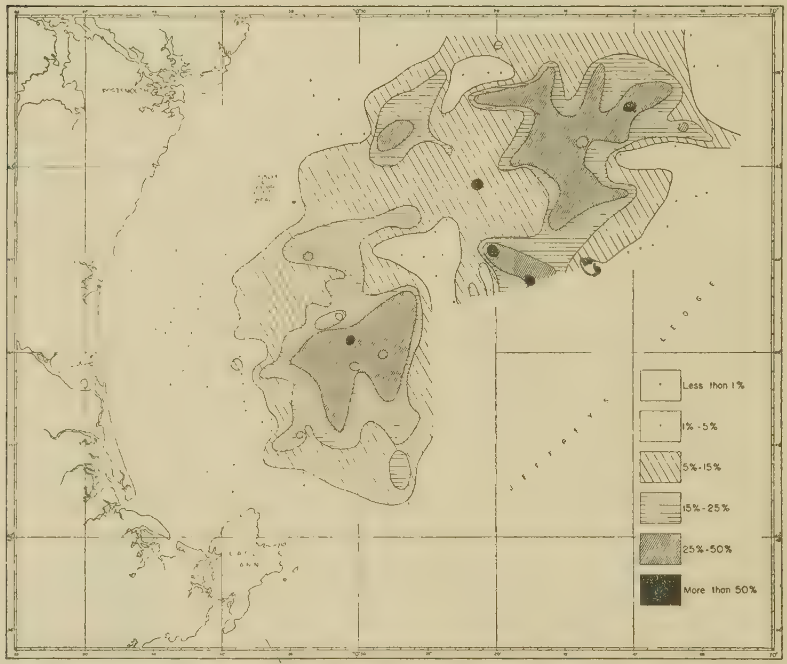

Figure 21. Distribution of *Reophax curtus* Cushman in per cent of total population of benthonic Foraminifera

Distribution of Living Fauna

The distribution of living Foraminifera was investigated in 213 samples. Study of living specimens was restricted to samples collected with the short coring tube, since these samples are the only ones which contain undisturbed sections of the surface of the sediment and in which specimens were preserved in formaldehyde. The short coring tube will only collect samples in sediment which contains sufficient mud to give it a certain amount of cohesiveness. The analysis of distribution of living populations in this area is restricted, therefore, to bottom sediments other than those of clean sand, gravel and rock.

The restricted distribution of samples for the living fauna should be kept in mind in evaluating the results.

All samples taken with the short coring tube cover an equal area of bottom and are approximately equal in size. Specimens were not examined alive but had been preserved in formaldehyde. The chemical color test used is one for the identification of protein. The use of this method for determining the presence of living specimens in this type of material involves the following assumptions: (1) that the presence of protein in the shell indicates the presence of protoplasm, and (2) the presence of protoplasm indicates that the specimen was either alive at the time it was collected or had been living only a short time previous to collection. It is believed that both these assumptions are valid.

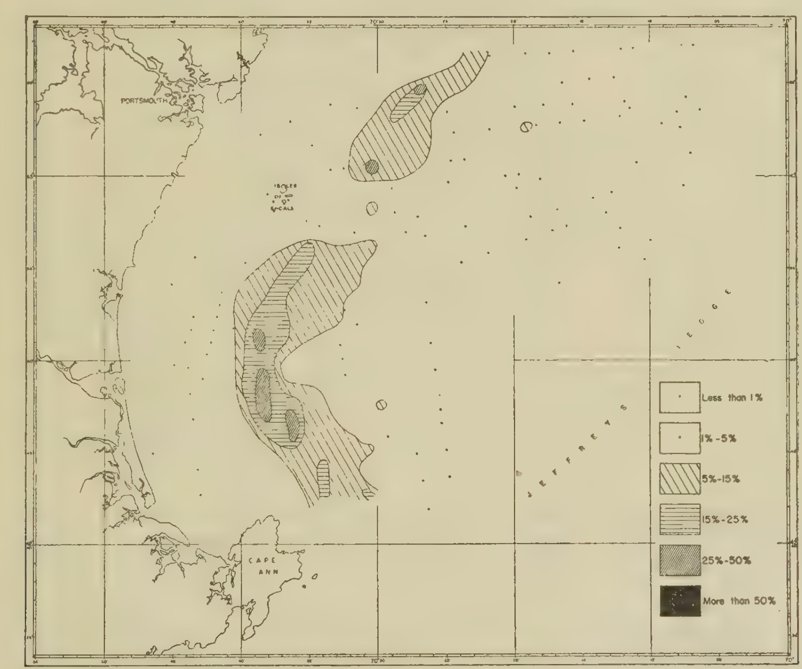

Figure 22. Distribution of *Reophax scottii* Chaster in per cent of total population of benthonic Foraminifera

Twenty-six species of Foraminifera were found living in the samples examined, or approximately 40 per cent of the total number of species reported from the bottom samples and all the species characteristic of mud and mud-sand areas. All the more common species were represented by living specimens except those species characteristic of the sand and gravel areas where no samples were collected for living specimens. The species found living are listed in Table 12 in decreasing order of abundance; the number of stations at which a species was found living is taken as a measure of its relative abundance in Table 12. Actual abundances in terms of percentage of total living population may be obtained from Tables 8 to 11.

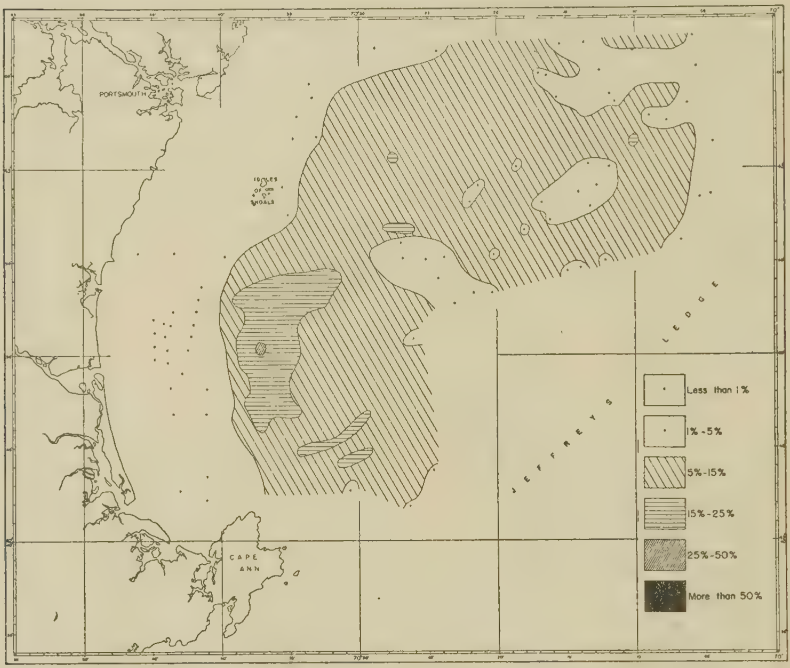

Figure 23. Distribution of *Spiroplectammina biformis* (Parker and Jones) in per cent of total population of benthonic Foraminifera

Frequencies of several of the most abundant living species have been plotted geographically, similar to the population plots in Figures 7 to 25. These unpublished plots show a good correlation between the distribution of the total population of each species and the distribution of the living representatives of that species. The areas of high concentration are the same for all species which have been analyzed. This is clearly seen in *Reophax arctica*, for example, where the only important abundance in total population is near the shoreward side of the southwest mud-sand area but it has a scattered low frequency elsewhere. Nine of the 14 occurrences of living specimens are grouped in the southwest mud-sand area and the remaining 5 occurrences are scattered. Both living and total populations of *Haplophragmoides bradyi* are essentially confined to the Portsmouth basin and none has been recorded from the southwest mud-sand area. The distribution chart of *Recurvoides turbinatus* shows an important concentration in the Portsmouth basin with scattered occurrences elsewhere; the living population of this species has the same geographic distribution.

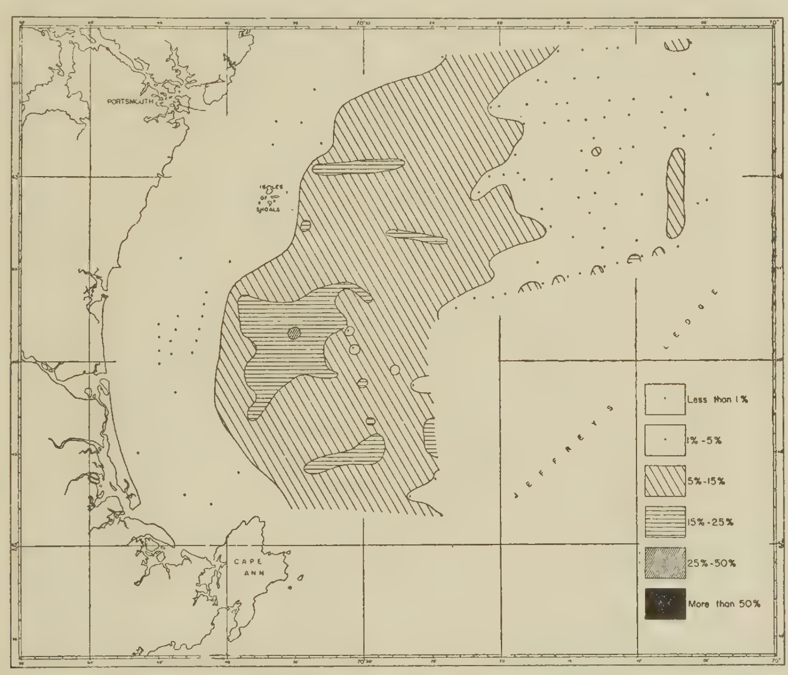

Figure 24. Distribution of *Textularia torquata* Parker in per cent of total population of benthonic Foraminifera

Eggerella advena which is characteristic of the inshore areas has living representatives only in 10 core samples taken from the shoreward edge of the mud-sand areas. The total population chart shows *Haplophragmoides glomeratum* to be abundant except on the inshore sand and gravel areas and the offshore sand areas; the distribution of living specimens of this species is similar and shows marked decrease in abundance shoreward in the southwest mud-sand area. The same samples or groups of samples have similar relative frequencies for living and total population of a species in many instances. This suggests no great post-mortem displacement of fauna in this region.

Distribution of total population of living Foraminifera is shown in Figure 6. There are three areas which have a relatively large standing population of living specimens: the Portsmouth basin, the seaward half of the southwest mud-sand area, and the northwest mud-sand area. It is of interest that there is a more or less regular decrease in living population in the southwest mud-sand area toward the shore.

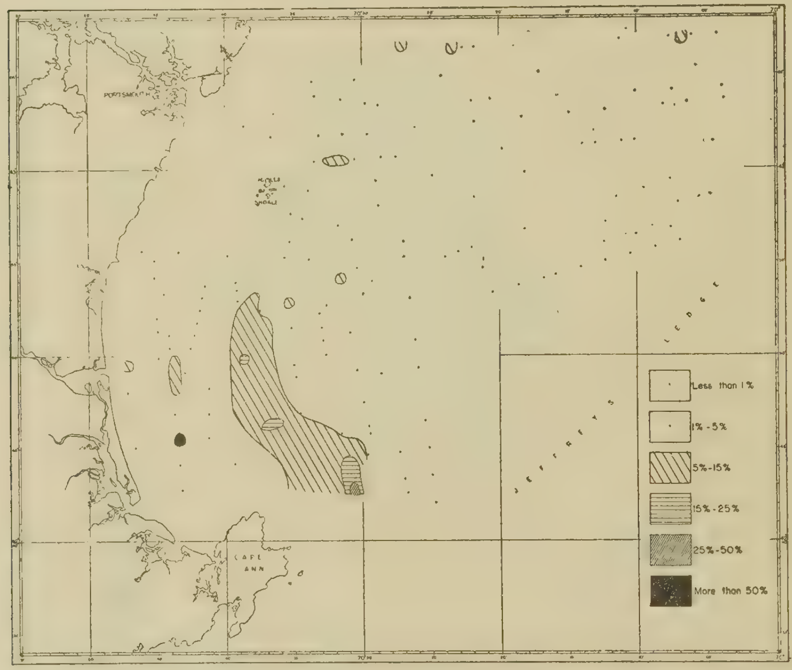

Figure 25. Distribution of *Trochammina squamata* Parker and Jones in per cent of total population of benthonic Foraminifera

It appears probable that the standing crop of benthonic Foraminifera is an index to the relative total production of benthonic organisms. The distribution of this population thus suggests that the three areas of largest population of empty tests are also the most productive. The population decrease shoreward in the southern part of the southwest silt area can be correlated with the increase of sand in the sediment and suggests that in some places mud in sediment is conducive to a relatively high population. Similar results have been obtained by

Phleger and Walton (1950) from Cape Cod Bay, off Barnstable, Mass., where there is an increase offshore with increasing mud content of the sediment.

The standing population of living benthonic Foraminifera can be converted into standard units of area for purposes of general comparison. The small coring tube samples an area which is about 9.7 sq. cm., or approximately one-thousandth of a square meter. The population distributions in the Portsmouth area suggest that the samples taken are representative of a much larger area since there are discrete areas of population intensity and recognizable population trends. The range in living population intensity in this area is approximately 1000/sq.m. to more than 100,000/sq.m., with populations greater than 50,000/sq.m. over relatively large areas in places of highest productivity.

It is of interest to note the variation in density of standing crop of Foraminifera in the southwest mud-sand area. In the offshore part of this area there is a living population up to more than 50,000/sq.m. and there is a regular decrease shoreward to less than 5000/sq.m. In the northern nearshore part of this mud-sand area there is a patch having a rather large living population, more than 25,000/sq.m. Examination of Figure 5 shows that there is a patch of a very high total population per sample south of the Isles of Shoals. The large standing crop at this place may be a reflection of high organic production to the south of the Isles of Shoals.

The only other region where comparable studies have been made on the distribution of living Foraminifera is in the northwest Gulf of Mexico (Phleger, 1951). Comparison may be made of the population density of living benthonic Foraminifera in the Portsmouth area with the population density on the continental shelf in the northwest Gulf of Mexico. The same type of sampler was used to obtain sediment materials in both areas and the ranges of depth are comparable. In the Gulf of Mexico the maximum number of living specimens at any station in any of the 12 traverses across the continental shelf is seldom greater than 25 and in some traverses is approximately 10, while most of the samples had fewer living specimens. The average number of specimens in the Gulf of Mexico area is 10.1/sample for 197 samples while at Portsmouth the average number is 31/sample for 213 samples. The approximate average standing crop is then 10,000/sq.m. in the northwest Gulf of Mexico and 30,000/sq.m. in the Portsmouth area.

Production rates of the Foraminifera may be a good index of the relative organic production in any area. This is believed probable because they are universally present, constitute a great variety of genera and species, and are all comparable in general size range of adults, except for the large forms common in calcareous areas. The standing crop of living specimens collected at any time, if representative of the area, is the result of the production which has occurred and is a clue to the population which the area will support. It would be desirable to collect seasonal samples over a period of years to obtain reliable results on relative production by the method of population sampling but this has not been possible up to the present time. The data given on the living Foraminifera populations suggest that the average production rate in the Portsmouth area is approximately three times as great as the average production rate on the continental shelf in northwest Gulf of Mexico. It would be interesting to examine living population distributions from other areas.

Foraminifera Facies

There are at least two principal faunal facies in the Portsmouth area, one developed on sand bottom (and "gravel") and the other developed on mud and mud-sand bottom. In addition there are one or more rather distinct subfacies present which can be recognized by the presence or high concentration of one species or a group of species. Certain species have overlap distributions and there are a few forms which are universally distributed throughout the area. The faunal constituents of these facies and subfacies are described below and the possible significance of the distributions is discussed in a later section.

Figure 26 is a generalized diagram of the distribution of most of the species occurring in the area. Six species are omitted from this figure and from the discussion because of their rarity. The sand facies in Figure 26 is separated into two divisions: the nearshore sand (and gravel) areas and the offshore sand areas. The mud facies, likewise, is separated into mud-sand areas and the Portsmouth basin, the principal mud area. The glacial till areas are not separately treated for practical reasons. The fauna on these areas is generally closely allied to that in mud and sand but occasionally sand facies species are present. These subdivisions, while somewhat arbitrary, bring out certain details of distribution which are considered important. The distributions as charted in Figure 26 are generalized on the basis of percentage frequency and relative number of stations at which a species is present. The three subdivisions of low frequency, intermediate frequency, and high frequency are intended as generalizations. The data on which these are based are found in Tables 2 to 7, in Figures 7 to 25, and in the written discussions of the distribution of the species.

Sand facies. The following species occur with high or intermediate frequencies on the sand facies and appear to be restricted to that facies:

- *Cassidulina algida*
- *Cibicides lobatulus*
- *Elphidium articulatum*
- *Elphidium incertum* var. *clavatum*
- *Elphidium subarcticum*

The following species are generally restricted to various sand areas and occur in low frequency:

- *Angulogerina angulosa*
- *Astrononion stellatum*
- *Bolivina pseudoplicata*
- *Bolivina subaenariensis*
- *Bulimina aculeata*
- *Buliminella elegantissima*
- *Discorbis columbiensis*
- *Discorbis squamata*
- *Eponides frigidus*
- *Miliammina fusca*
- *Nonion labradoricum*
- *Patellina corrugata*
- *Pseudopolymorphina novangliae*
- *Quinqueloculina arctica*
- *Quinqueloculina subrotunda*
- *Quinqueloculina seminula*
- *Triloculina tricarinata*
- *Trochammina inflata*
- *Trochammina lobata*
- *Trochammina macrescens*
- *Virgulina complanata*
- *Virgulina fusiformis*

Eggerella advena is abundant on sand areas, especially the inshore areas, but is present in low frequencies on other bottom types. *Labrospira crassimargo* is especially characteristic of the mud facies but does occur in rather high frequencies on some offshore sand areas. *Reophax scottii* is of very high frequency throughout the mud facies but occurs in appreciable numbers at many of the stations in the sand facies.

Distribution of four rare species appears to be related to the mouth of the Merrimack River, being essentially restricted to areas off the river mouth or to the south of it.

These species are:

- *Discorbis squamata*
- *Miliammina fusca*
- *Trochammina macrescens*
- *Trochammina inflata*

SPECIES	SAND FACIES		MUD FACIES	
	Nearshore Sand Areas	Offshore Sand Areas	Mud-sand Areas	Portsmouth Basin
Ammobaculites cassis	- - -	- - -	- - -	- - -
Ammodiscus ssp.	———	———	———	———
Angulogerina angulosa	- - -	- - -		
Astrononion stellatum	- - -	- - -		
Bolivina pseudo-plicata	- - -			
B. subaenariensis		–		
Bulimina aculeata	- - -	- - -		
Buliminella elegantissima	- - -			
Cassidulina algida	━━━	━━━		
Cibicides lobatulus	━━━	———		
Crithionina pisum var. hispida			- -	- - -
Discorbis columbiensis	- - -	- - -		
D. squamata	- - -			
Eggerella advena	━━━	━━━	- - -	- - -
Elphidium articulatum	———	———		
E. incertum var. clavatum	━━━			
E. subarcticum	━━━			
Eponides frigidus	———	- - -		
Globobulimina auriculata	- - -	- - -		
Glomospira gordialis	- - -	- - -	- - -	- - -
Haplophragmoides bradyi				━━━
H. glomeratum	- - -	- - -	━━━	━━━
Hippocrepina indivisa			- - -	- - -
Hyperammina elongata		———	———	———
Labrospira crassimargo	- - -	━━━	━━━	━━━
L. jeffreysii		———	━━━	━━━
L. cf. nitida				- - -
Miliammina fusca	- - -			
Nonion labradoricum	- - -	- - -		
Patellina corrugata	- - -	–		
Proteonina atlantica	━━━	━━━	━━━	━━━
Quinqueloculina arctica	- - -			
Q. frigida	- - -		- - -	
Q. seminula	- - -	–		
Q. subrotunda	- - -			
Recurvoides turbinatus	- - -	- - -	———	━━━
Reophax arctica	———	- - -	- - -	- - -
R. curtus	- - -	- - -	━━━	━━━
R. scottii	- - -	- - -	━━━	- - -
Spiroplectammina biformis	- - -	- - -	━━━	━━━
S. typica	- - -	- - -	- - -	- - -
Triloculina tricarinata	- - -	- - -		
Trochammina advena				———
T. inflata	- - -			
T. lobata	———	- - -		
T. macrescens	–			
T. quadriloba			- - -	———
T. squamata	———	———	━━━	———
Valvulina conica	- - -	- - -	- - -	———
Virgulina complanata		- - -		
V. fusiformis	- - -	- - -		
Textularia torquata	- - -	- -	━━━	

Figure 26. Generalized distribution of Foraminifera according to sedimentary facies. Heavy lines indicate most abundant; solid thin lines indicate intermediate abundance; dashed lines indicate lowest relative abundance.

Eggerella advena also has its greatest frequency in the nearshore sand south of the Merrimack River where it is the dominant member of the fauna at many stations. *Quinqueloculina arctica*, on the other hand, is found in this facies only north of the Merrimack River.

Cibicides lobatulus is the dominant member of the fauna off the Isles of Shoals and Hampton Beach. *Discorbis columbiensis* also has its greatest frequency off Hampton Beach. These are forms which live attached to weed, rocks, shells, etc. Their abundance in this area undoubtedly is to be correlated with the presence of rocky, stony, shelly, and coarse sand bottom. These bottom types furnish good attachment for the large marine algae and also probably attachment for these two species.

The following species appear to be restricted to the inshore sand areas and generally are not present on the offshore sand areas:

Elphidium incertum var. *clavatum*
E. subarcticum
Bolivina pseudo-plicata
Buliminella elegantissima
Discorbis squamata
Miliammina fusca
Quinqueloculina arctica
Q. subrotunda
Trochammina inflata

Virgulina complanata was only found in offshore sand areas. *Bolivina subaenariensis* was found only at one station on an offshore sand area.

Mud facies. The following species have high frequencies in the mud facies and are especially characteristic of that facies although most of them are present in lower frequencies at many stations in the sand facies:

Haplophragmoides bradyi
H. glomeratum
Labrospira crassimargo
L. jeffreysii
Recurvoides turbinatus
Reophax curtus
R. scottii
Spiroplectammina biformis
Textularia torquata

The following species are restricted to the mud facies but are relatively low in frequency:

Crithionina pisum var. *hispida*
Hippocrepina indivisa
Labrospira cf. *nitida*
Trochammina advena
T. quadriloba

Labrospira nitida and *Trochammina advena* are essentially restricted to the Portsmouth basin. *Haplophragmoides bradyi* occurs in rather high frequencies and is also restricted to the Portsmouth basin and its borders. *Crithionina pisum* var. *hispida* is largely restricted to the Portsmouth basin but also is present at a few stations in mud and sand. *Trochammina squamata* has its highest frequency in the southwest mud-sand area and it may be especially characteristic of mud-sand bottom sediment; this species is rather universally distributed throughout the area on all types of sediment but in lower frequencies.

Reophax scottii is especially characteristic of the mud-sand areas and reaches its greatest abundance near the shoreward edge of the southwest mud-sand area; it also occurs at very low frequency in several other samples.

Textularia torquata reaches its highest frequency in the mud-sand areas.

There is an additional group of species which are universally distributed in the Portsmouth area. *Proteonina atlantica* is the most abundant of these universal species; this species is perhaps the most characteristic one for the area as a whole. The following forms are of lower frequencies but are universally distributed:

Ammobaculites cassis
Ammodiscus
Glomospira gordialis
Spiroplectammina typica

Reophax arctica also is of universal distribution, at low frequencies, but has a slightly greater local abundance in the southwest sand area.

FORAMINIFERA IN SHORT CORES

The vertical distribution of Foraminifera was studied from 18 of the short cores which were taken from the mud facies area, and comprising 174 separate samples. The Foraminifera were examined from the bottom samples of approximately 30 additional cores. Many of the short mud cores contain a somewhat different sediment in the lower section than in the upper section, especially those taken from the vicinity of the Portsmouth basin. In the upper part of these cores the sediment is of predominantly silt sizes and may be described as a soft mud; the lower section has clay sizes predominating and has a clay-like plasticity in many samples.

The upper fauna in the cores is described in the previous section. The lower fauna is quite distinctive from the upper one and may be characterized as a calcareous fauna, in which the greatest number of specimens and of species are of various calcareous Foraminifera. This is remarkably different from the upper core fauna in the mud facies which is composed almost exclusively of arenaceous species.

The lower core fauna, at most stations examined, is dominated by *Globobulimina* (*Desinobulimina*) *auriculata* and *Nonion labradoricum* which together usually constitute more than 50 per cent of the fauna. The following calcareous species are somewhat less abundant but constitute an important element of the lower fauna in a large number of samples:

Cassidulina algida
C. islandica var. *minuta*
C. norcrossi
Elphidium incertum var. *clavatum*
Eponides frigidus
Virgulina complanata

The following calcareous species are lower in general frequency:

Angulogerina angulosa
Astrononion stellatum
Bolivina subaenariensis
Bulimina aculeata
Cibicides lobatulus
Elphidium articulatum
Nonionella auricula
Pullenia bulloides
Pyrgo subsphaerica
Quinqueloculina seminula
Q. subrotunda
Robertina cf. *charlottensis*
Virgulina fusiformis

The following arenaceous species are present in the lower fauna but usually are of considerably lower frequency than in upper samples of the same cores:

Eggerella advena
Haplophragmoides glomeratum
Labrospira crassimargo
L. jeffreysii
Proteonina atlantica
Reophax curtus
Spiroplectammina biformis
Textularia torquata
Trochammina squamata

Proteonina atlantica is the most prevalent arenaceous species in the lower fauna.

All the species in the lower core fauna are living in the Portsmouth area at the present time except *Pullenia bulloides*, *Cassidulina islandica* var. *minuta*, and *Robertina* cf. *charlottensis*; these three species may exist in the area but were not discovered in the samples collected. All the calcareous species characteristic of the lower fauna are at present confined to the sand facies areas. The lower fauna arenaceous species are at present characteristic of the mud facies and do not occur in any abundance in the sand facies; *Proteonina atlantica* is an exception, common in both facies.

Specimens of planktonic Foraminifera were found in a few samples containing the lower core fauna in 15 of the 18 cores studied, although no planktonic species occurred in the upper fauna from the same cores. *Globigerina bulloides* is the most common species in these samples and the following additional planktonic species are present:

Globigerina inflata
G. eggeri
G. pachyderma
G. sp.
Globorotalia scitula

The distribution of these species in the cores can be obtained by examining Tables 13 to 18.

DISCUSSION

Field and Laboratory Methods

One of the perennial problems in marine sedimentology is whether a small sample of sediment taken by means of one of several different sampling devices is characteristic of the much larger area it is presumed to represent. This is a complex problem with variables. In the Portsmouth area the distribution of Foraminifera populations can be used as an indirect method of determining the accuracy of the sampling methods and spacing.

A study of the population patterns for different species on Figures 7 to 25 shows that they have distributions which appear to be reasonable for marine organisms. An examination of the areal chart of *Reophax curtus* (Fig. 21) may be used as an example. There are three large areas of high frequency of *R. curtus* in the principal areas of the mud facies where this species constitutes more than 25 per cent of the population, and there is a gradual decrease in frequency in all directions away from these centers. The actual frequency data show that the samples fall naturally into areal units which can be plotted, and are not distributed in a haphazard manner. *Eggerella advena* (Fig. 9) may be taken as an example of a sand facies species; it is most abundant on the southwest sand area and the numerous records of its occurrence show a regular decrease in abundance toward the southwest mud-sand area. Examination of areal plots of all the species shows that the distributions are naturally grouped so that they comprise areal units which can be mapped and which can be explained on theories of areal radiation of marine organisms. The consistency of these data indicates that the type and distribution of the samples give a good picture of the distribution of faunal variables in the area covered.

It is unfortunate that it was necessary to use different types of sampling gear in this area because of the variation in nature of the sediments. The short coring tube collects an undisturbed sample which has a constant area and in which the size and thickness of the surface sample can be controlled easily. Moreover, the actual surface of the sediment is a part of the sample. The orange-peel dredge, on the other hand, collects a sample, variable in size, which comes from a varying depth within the sediment; the sediment has had little general mixing although there is some disturbance due to washing en route to the surface of the water or on transferring the material on board ship. The material collected by the Stetson-Iselin sampler is not washed en route to the surface, since it is sealed in the collecting tube, but it is thoroughly mixed while being extracted from the tube; this gear collects a sample which varies in size and which includes a variable area and thickness of sediment. The samples for study taken from the orange-peel dredge and from the Stetson-Iselin sampler were roughly equal in size to those studied from the core samples. It was not convenient to make them actually equivalent in size due to the difficulty of judging size of sediment samples, and some samples may be a little larger than others. This probable size inequality does not affect percentage distribution of species but may reduce the reliability of the total population data for the sand facies areas.

The desirability of using species instead of genera in ecological studies of Foraminifera is well demonstrated by the present results. The advantages of a relative frequency system in percentage of total fauna in recording occurrences also are demonstrated. Both these principles may be illustrated by distribution of the species of *Trochammina* and *Haplophragmoides,* and to a lesser extent by the *Labrospira* species. *Trochammina squamata* is most characteristic of the mud-sand areas and is present in greatly reduced percentages on other types of sediment; *T. quadriloba* occurs on mud-sand and mud; *T. advena* is confined to the Portsmouth basin; *T. lobata* is confined to the sand facies; and *T. macrescens* is reported only from the sand facies. If the genus as a whole had been treated without regard for the various species, the conclusion would have been that *Trochammina* is generally characteristic of the entire area although it has a somewhat higher frequency on the mud facies. *Haplophragmoides glomeratum* occurs in the entire area but is extremely abundant on all mud facies areas; *H. bradyi* is restricted to the mud of the Portsmouth basin where it is quite abundant. *Labrospira jeffreysii* is abundant throughout the mud facies; *L.* cf. *nitida*, while rare, is confined to the Portsmouth basin.

It is believed that the methods of taking the census of the living population give a true distribution picture. This evaluation is based largely on the good correlation between the population frequencies of empty tests and living specimens of the same species. The major contributions of this technique are considered to be: (1) establishing the amount of standing crop and thus establishing a means for comparative production studies on this basis, (2) demonstration that a species is living in the area where it is found, and (3) collection of data which eventually will make it possible to estimate relative rates of deposition.

Relationships of the Modern Fauna

It is of interest to attempt to place the geographic affinities of the fauna from this area. Cape Cod is the most effective temperature and thus ecologic barrier along the northern part of the east coast of the United States and effectively limits the north-south distribution. Any attempt to summarize the distribution of modern species of Foraminifera is beset by the following handicaps: (1) there has been insufficient study of faunas throughout the world to establish more than a general idea of distribution of these forms, and (2) the determination of species in many faunal records is either inaccurate or the reliability of identifications cannot be assessed because of insufficient data given with the reports. The general paucity of reliable frequency data on distribution records should also be indicated.

The Portsmouth fauna may be divided into 3 groups of species for determining geographic affinities. One group of species occurs only north of Cape Cod and is principally known from the Arctic; a second group is known only from south of Cape Cod; and a third group is present in both regions.

The following Portsmouth area species have been reported only from north of Cape Cod and principally from Arctic regions:

Ammobaculites cassis
Astrononion stellatum
Cassidulina algida
C. islandica var. *minuta*
Labrospira jeffreysii
Nonion labradoricum
Recurvoides turbinatus
Reophax arctica
Trochammina quadriloba

Nonionella turgida and *Cassidulina islandica* var. *minuta* are found only in the lower core fauna.

The following Portsmouth area species also are reported only from south of Cape Cod and are not recorded from the Arctic:

Ammodiscus minutissimus
Elphidium advenum var. *margaritaceum*
E. articulatum
E. excavatum
Eponides umbonatus
Haplophragmoides bradyi
Labrospira cf. *nitida*
Miliammina fusca
Pyrgo subsphaerica
Reophax scottii
Trochammina advena
T. lobata
T. macrescens

The remainder of the species are known in both areas.

Considerably more is known of the Foraminifera faunas from south of Cape Cod than from the Arctic. The absence of records of a species from south of Cape Cod therefore suggests somewhat greater reliability than its absence from the Arctic. In general the species previously known only from south of Cape Cod are more rare at Portsmouth than those characteristic of the Arctic. These data suggest that the Portsmouth fauna may be considered somewhat intermediate between the continental shelf fauna immediately south of Cape Cod and the Arctic fauna and further suggest that the general affinity is perhaps more with the Arctic assemblage than with the southern one. It is quite possible that the southern extent of the Arctic forms may be somewhat more critical than the northern distribution of southern types, for reasons already given. The group of species which are distributed through a wide range of latitude are considered to be those which have a wide range of temperature tolerance. The fauna of the Portsmouth area is considered to be on the southern fringe of Arctic affinities.

Significance of Facies Distribution

Distribution of the Foraminifera in rather discrete facies which can be correlated with sediment type is a striking fact in the Portsmouth area. Any attempt to explain the distribution requires analysis of all the environmental conditions which are sufficiently well-known to be significant in this discussion.

It is shown in a preceding section that the temperature cycle is relatively uniform within the area. It is quite clear however, that some parts of the area may be expected to have somewhat different temperature cycles if conditions of the bottom water only are considered. The inshore water, shallower than 30 to 50 m., is expected to have the greatest yearly temperature range, from a monthly mean minimum of about 2°C to a maximum of about 18°C. The deep area of the Portsmouth basin, on the other hand, has relatively little seasonal temperature range, approximately 3°C to 6°C. The same low temperature range obtains for any part of the area having a depth greater than about 60 to 75 m. This greater depth range includes the mud-sand areas, some of the glacial till, and all of the mud facies. The seaward boundary of the inshore sand in the southwest part of the area approximately coincides with the 60 m. contour. The offshore sands, especially those on Jeffreys Ledge appear to extend to somewhat greater depth; it is suggested that some of this extended depth range may be due to mass movement of material along the rather steep slopes on the seaward side of the Portsmouth basin. It is apparent that the sand facies contains the Foraminifera which are adapted to pronounced seasonal ranges of temperature, as indicated, and the mud faunal facies is one adapted to lower temperatures and smaller seasonal range.

The salinity is relatively uniform for the area except for the general decrease shoreward and the somewhat higher salinity in the deeper parts of the area. The nearshore sand areas have a somewhat lower seasonal salinity minimum but this would not apply to the offshore sand areas where the salinity is uniform throughout the year. This relatively lower salinity may be of some importance in the ecology of the nearshore sand facies. The species which are confined to the nearshore sand, listed above, may be in part limited by salinity factors. *Trochammina inflata, T. macrescens,* and *Miliammina fusca,* listed as three of the species occurring on the nearshore sand only south of the Merrimack River, are also reported from the Barnstable, Massachusetts, area by Phleger and Walton (1950). In the latter area they are characteristic only of the marsh area and only occasional specimens are found outside the marsh where they appear to have been carried by tidal currents. It is suggested that these species in the Portsmouth area probably were carried out of marshes adjacent to the southern part of the coast and do not reflect ecologic conditions at the few localities where they were collected. Their occurrence here is thus believed due to the proximity to large areas of marsh and the presence of strong tidal currents which provide adequate transportation.

The depth ranges of several of the species from the Portsmouth area are known from Parker's work on the continental shelf (1948). The following species restricted to the sand facies are characteristic of Parker's Zone 2, with a lower depth limit of about 90m:

Elphidium incertum
E. subarcticum
Bolivina pseudoplicata
Trochammina lobata
Quinqueloculina seminula

The following sand facies species occur in Parker's Zone 3 which is deeper than 90m:

Virgulina fusiformis
Bolivina subaenariensis
Bulimina aculeata
Nonion labradoricum
Globobulimina (Desinobulimina) auriculata

Eggerella advena, which is so abundant in the inshore sand facies, is listed by Parker as ranging to a maximum depth of 121m. The following mud facies species are reported as occurring in Parker's Zone 3 and not in Zone 2:

Haplophragmoides glomeratum
Valvulina conica

Buliminella elegantissima, a sand facies species, is restricted to depths less than about 100m., in the northwest Gulf of Mexico according to Phleger (1951). *Haplophragmoides glomeratum* and *H. bradyi* occur at all ranges of depth greater than about 100m. in the northwest Gulf of Mexico.

These comparisons demonstrate that some of the species present in the Portsmouth area have similar depth ranges in other regions. It is possible that additional information of Foraminifera depth ranges in the North Atlantic will show additional correlations. It should be indicated that essentially nothing is known about depth ranges or any other distribution factors from Arctic regions, and since the Portsmouth fauna contains many Arctic elements, depth comparisons are thus made more difficult. It is the opinion of the writer that there is as significant depth zonation in the present area as for areas elsewhere.

The distribution records of the few Portsmouth species which occur in the Barnstable, Massachusetts, area and in the Long Island Sound-Buzzards Bay area have been examined for type of sediment providing the substratum for the species in those areas. The habitat of the same species in these other areas is not especially characteristic of particular types of bottom. Two outstanding exceptions are *Cibicides lobatulus* which may be largely restricted to sand and *Reophax scottii* which is largely restricted to mud. The presence of the modern sand facies species in the fine-grained mud of the lower parts of the short cores from the present area is evidence in this connection. It seems probable that sediment type has little or no effect, in itself, upon the distribution of most of the Foraminifera species in the Portsmouth area.

The Core Faunas

The most important general features of the core faunas are the striking differences between the upper and lower faunas and the fact that the lower core faunas are essentially the same as that of the modern sand facies. The boundary between the two faunas is rather sharp in many of the cores. It is of interest to speculate on the causes for virtual elimination of the present sand facies from the mud facies areas, although a completely satisfactory explanation is difficult or impossible at the present stage of our knowledge.

The faunal change with time appears to have been rather abrupt on the mud facies areas if the core data are correctly interpreted. This implies some rapid change of environmental conditions which eliminated the calcareous species of the lower core fauna from the mud and mud-sand areas. The repopulation of the mud facies areas with a completely arenaceous assemblage may have been accomplished in either of two ways: either the arenaceous species were introduced from outside the area or they survived the change in environment and increased in abundance in the available habitats.

The calcareous fauna may have invaded and populated the sand facies areas because it was either the only available environment or because the environment was more suited to their survival and proliferation. It is possible that the arenaceous species became so abundant in mud areas that they exerted sufficient population pressure to exclude other forms. It appears, however, that the redistribution of faunas probably was connected with rise of sea level during the late glacial or post-glacial time. As the water deepened over the mud areas the environment may have become less desirable for the calcareous species which were adjusted to environments in the upper water layers and they gradually invaded the newly opened environment of the present sand facies. It is suggested above that the facies distribution is largely controlled by ecologic factors associated with depth. It is reasonable, therefore, that the shallow-water calcareous species would in general be excluded from the areas which were deepening and invade more congenial shallow areas.

The arenaceous species which were already present as a minor element of the population in the mud facies areas greatly increased in abundance and became essentially the entire mud facies fauna. A few arenaceous species, apparently well-adapted to both the principal environments in the Portsmouth area, migrated into the shallow-water areas in appreciable quantity. Other arenaceous species became approximately as abundant on the modern sand facies as they were in the mud facies at a time when sea level was lower.

It is suggested that even the lower core fauna lived in the Portsmouth area some time after the local large-scale melting of the glacial ice. Ice melting in any quantity in this area would have introduced large amounts of fresh water into the Gulf of Maine and would have caused brackish conditions. The assemblage in the lower core fauna contains no species particularly characteristic of brackish water. Longer cores are desirable from this area and from other parts of the Gulf of Maine to obtain further details of the late glacial and post-glacial history of this marine area.

SUMMARY OF CONCLUSIONS

1. Population patterns of Foraminifera species in the Portsmouth area show discrete areal units which can be mapped and which appear to be reasonable. This suggests that the sampling was representative of the area.
2. The modern Foraminifera fauna of the Portsmouth area is related to the Arctic fauna, although it contains elements also found south of Cape Cod.
3. There are two principal faunal facies. One facies is characteristic of sand areas and extends to an average depth not greater than about 60 to 75m. The other facies is developed on mud and mud-sand areas at greater depths. Some species are further restricted to mud, to sand-mud, and to inshore sand. Other species occur in uniform frequency throughout the area.
4. Chief causes for the facies distribution are believed to be ecologic factors related to water depth, principally the seasonal temperature ranges, but also salinity and numerous other factors. Salinity variations may be especially important from the mouth of the Merrimack River southward.
5. Distribution frequencies of the living fauna are comparable to

distribution frequencies of the empty tests, both of the total population and of individual species. The standing crop of living Foraminifera on the mud facies areas ranges from approximately 1000/sq.m. to more than 100,000/sq.m. The average living population was approximately 30,000/sq.m., or about 3 times as great as the average living population in nearshore areas of the northwest Gulf of Mexico.

6. The lower fauna of short cores from the mud facies areas is dominated by calcareous species, with arenaceous species in very low frequencies, the same fauna which at present lives on sand facies areas. The upper core fauna is composed of arenaceous species. It is suggested that the lower fauna lived on the present mud facies areas when the water there was shallower, that it migrated into the sand facies areas during post-glacial rise of sea level, and the arenaceous species remained in deeper waters where the environment was conducive to their proliferation.

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Contribution No. 591, Woods Hole Oceanographic Institution.

Contribution No. 6, Marine Foraminifera Laboratory.

Table 1

Location of Stations

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
2	43°00.9′	70°23.8′	110
5	42°58.2′	70°22.0′	106
8	42°55.4′	70°20.2′	148
14	42°53.4′	70°21.8′	129
18	43°05.0′	70°16.4′	144
21	43°03.6′	70°11.4′	172
22	43°03.2′	70°10.2′	162
23	43°02.8′	70°08.9′	152
24	43°02.5′	70°07.6′	143
25	43°02.1′	70°06.3′	143
27	43°01.4′	70°04.2′	104
28	43°01.1′	70°06.8′	157
29	43°00.6′	70°10.8′	175
30	43°00.2′	70°13.4′	208
31	42°59.8′	70°16.0′	160
33	42°59.1′	70°21.3′	122
34	42°52.6′	70°32.6′	95
35	42°51.9′	70°31.5′	104
36	42°51.6′	70°31.1′	112
40	42°49.8′	70°28.3′	116
41	42°49.5′	70°27.8′	107
42	42°49.2′	70°27.1′	108
48	43°03.5′	70°24.8′	95
50	43°03.5′	70°23.4′	100
52	43°03.6′	70°21.9′	107
53	43°03.6	70°21.1′	110
54	43°03.6′	70°20.4′	119

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
55	43°03.7′	70°19.8′	125
58	43°03.7′	70°17.7′	143
61	43°03.8	70°15.6′	158
62	43°03.9′	70°14.8′	162
65	43°03.0′	70°13.5′	168
67	43°02.0′	70°12.9′	172
68	43°01.5′	70°12.6′	171
71	43°00.1′	70°11.8′	180
73	42°59.1′	70°12.1′	183
74	42°59.0′	70°12.7′	182
76	42°58.7′	70°14.1′	166
80	42°58.1′	70°16.7′	152
82	42°57.7′	70°18.7′	146
85	42°56.5′	70°24.4′	114
88	42°56.7′	70°26.5′	100
90	42°56.9′	70°28.0′	93
91	42°56.1′	70°35.2′	66
96	42°54.1′	70°31.6′	88
97	42°53.7′	70°31.5′	94
98	42°53.2′	70°31.4′	96
102	42°51.3′	70°30.8′	117
103	42°50.6′	70°30.7′	110
104	42°50.1′	70°30.5′	109
105	42°49.7′	70°30.4′	108
106	42°49.2′	70°30.3′	107
107	42°48.7′	70°30.2′	105
110	42°47.4′	70°29.8′	99
111	42°47.0′	70°29.7′	98
112	42°46.6′	70°29.6′	96

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
113	42°46.2′	70°29.4′	94
114	42°45.7′	70°29.3′	93
116	42°44.8′	70°29.3′	87
118	42°45.2′	70°30.7′	90
121	42°45.9′	70°32.5′	89
123	42°46.0′	70°33.8′	90
128	42°46.3′	70°37.1′	76
131	42°46.9′	70°38.3′	73
132	42°47.4′	70°38.4′	74
133	42°47.9′	70°38.5′	73
134	42°48.3′	70°38.5′	76
135	42°48.9′	70°38.5′	75
136	42°49.4′	70°38.6′	73
137	42°49.9′	70°38.7′	73
138	42°50.9′	70°38.7′	70
139	42°51.4′	70°38.9′	69
141	42°52.4′	70°39.0′	67
142	42°52.9′	70°39.1′	65
143	42°53.4′	70°39.2′	64
144	42°54.0′	70°39.2′	61
148	42°53.1′	70°37.6′	74
149	42°52.4′	70°37.5′	76
150	42°51.7′	70°37.4′	76
151	42°51.0′	70°37.3′	78
152	42°50.3′	70°37.2′	81
153	42°49.7′	70°37.0′	80
154	42°49.0′	70°36.9′	82
155	42°48.3′	70°36.8′	85
156	42°47.7′	70°36.7′	82

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
157	42°47.0′	70°36.6′	82
158	42°46.4′	70°36.5′	79
159	42°45.7′	70°36.3′	76
160	42°45.0′	70°36.2′	72
161	42°42.8′	70°34.0′	64
162	42°43.5′	70°34.1′	67
163	42°44.2′	70°34.2′	73
164	42°44.8′	70°34.3′	81
165	42°45.5′	70°34.4′	86
166	42°46.2′	70°34.5′	88
167	42°46.9′	70°34.5′	92
168	42°48.2′	70°34.7′	100
169	42°48.9′	70°34.8′	98
170	42°49.6′	70°34.9′	96
173	42°51.6′	70°35.2′	87
175	42°52.9′	70°35.3′	80
176	42°57.4′	70°34.2′	64
178	42°55.2′	70°33.8′	73
181	42°52.3′	70°33.0′	90
182	42°51.5′	70°32.9′	98
183	42°50.8′	70°32.7′	92
184	42°50.1′	70°32.5′	92
185	42°49.4′	70°32.4′	92
186	42°48.5′	70°32.2′	99
190	42°45.7′	70°31.5′	92
192	42°44.2′	70°31.1′	86
194	42°42.8′	70°30.8′	76
196	42°55.2′	70°35.6′	67
197	42°57.5′	70°35.2′	46

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
201	42°56.9′	70°31.7′	64
203	42°56.1′	70°30.7′	89
205	42°54.7′	70°30.3′	84
207	42°53.3′	70°29.8′	150
213	42°49.0′	70°28.5′	109
215	42°47.6′	70°28.1′	100
219	42°44.8′	70°27.2′	85
221	42°43.3′	70°26.7′	78
222	42°42.6′	70°26.5′	70
223	42°41.7′	70°26.2′	49
224	42°42.1′	70°24.5′	58
226	42°43.5′	70°24.7′	82
228	42°45.0′	70°25.0′	87
230	42°46.4′	70°25.3′	99
231	42°47.2′	70°25.4′	100
234	42°49.4′	70°25.8′	122
236	42°50.9′	70°26.0′	122
239	42°53.1′	70°26.4′	131
242	42°55.3′	70°26.8′	59
243	42°56.1′	70°26.9′	64
246	42°55.5′	70°28.7′	65
247	42°55.2′	70°25.2′	73
248	42°55.3′	70°23.8′	70
249	42°55.5′	70°22.9′	111
250	42°55.8′	70°21.9′	132
253	42°56.5′	70°19.0′	143
254	42°56.7′	70°18.1′	145
255	42°57.0′	70°17.1′	148
256	42°57.2′	70°16.1′	152

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
259	42°58.0′	70°13.2′	174
261	42°58.5′	70°11.3′	174
263	42°58.9′	70°09.4′	174
265	42°59.4′	70°07.4′	174
270	43°05.8′	70°02.8′	51
271	42°59.1′	70°02.3′	67
273	42°58.8′	70°03.8′	88
274	42°58.7′	70°04.5′	100
275	42°58.5′	70°05.2′	110
277	42°58.2′	70°06.8′	127
284	42°57.1′	70°12.1′	171
287	42°56.6′	70°14.4′	162
310	42°48.2.	70°41.2′	43
312	42°46.9′	70°41.1′	41
314	42°45.6′	70°41.1′	40
315	42°43.5′	70°41.1′	31
317	42°42.2′	70°41.1′	26
319	42°40.9′	70°41.1′	13
320	42°42.5′	70°39.3′	34
322	42°44.0′	70°39.2′	37
334	42°49.1′	70°42.9′	38
335	42°50.4′	70°42.5′	41
336	42°51.5′	70°42.3′	43
337	42°51.7′	70°42.0′	43
338	42°52.4′	70°41.9′	42
339	42°53.1′	70°41.7′	50
340	42°53.7′	70°41.5′	56
342	42°55.6′	70°43.5′	34
350	42°54.2′	70°45.1′	30

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
353	42°52.1′	70°45.1′	32
354	42°51.3′	70°45.0′	32
355	42°50.6′	70°45.0′	30
356	42°49.8′	70°45.0′	29
363	42°44.8′	70°44.7′	21
372	42°42.7′	70°43.1′	21
374	42°44.1′	70°43.3′	27
376	42°45.5′	70°43.5′	27
378	42°47.0′	70°43.7′	31
380	42°48.3′	70°43.8′	34
382	42°49.7′	70°44.0′	37
383	42°50.4′	70°44.1′	37
384	42°51.1′	70°44.2′	35
385	42°51.8′	70°44.3′	36
386	42°53.3′	70°44.5′	35
388	42°53.7′	70°43.4′	35
389	42°53.0′	70°43.5′	35
390	42°52.4′	70°43.6′	37
391	42°51.7′	70°43.7′	36
392	42°51.2′	70°46.1′	28
393	42°51.0′	70°46.8′	26
395	42°55.6′	70°46.1′	21
397	42°54.4′	70°46.7′	20
402	42°49.5′	70°47.2′	22
404	42°48.0′	70°47.1′	20
406	42°46.5′	70°46.8′	17
408	42°45.1′	70°46.5′	12
410	42°43.4′	70°45.6′	9
420	42°58.4′	70°44.5′	11

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
439	43°02.2′	70°38.6′	23
451	43°00.3′	70°38.2′	25
453	42°59.1′	70°38.2′	20
466	42°55.4′	70°39.8′	56
472	42°59.1′	70°35.6′	38
474	42°58.9′	70°33.9′	58
478	42°58.3′	70°30.5′	87
480	42°58.0′	70°28.8′	73
482	42°57.8′	70°27.0′	97
486	42°57.2′	70°23.5′	118
494	42°59.3′	70°19.7′	144
496	42°59.8′	70°18.0′	152
506	43°00.1′	70°18.5′	148
507	43°00.3′	70°19.5′	137
508	42°60.0′	70°20.5′	128
512	42°59.6′	70°24.6′	100
516	42°59.3′	70°29.0′	88
520	43°00.4′	70°33.5′	59
521	43°00.4′	70°32.5′	69
522	43°00.5′	70°31.5′	79
523	43°00.5′	70°30.5′	84
525	43°00.6′	70°28.5′	85
526	43°00.7′	70°27.6′	97
528	43°00.7′	70°25.6′	96
529	43°00.8′	70°24.6′	105
530	43°00.8′	70°23.6′	110
531	43°00.9′	70°22.6′	113
533	43°01.0′	70°20.6′	128
534	43°01.0′	70°19.6′	134

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
535	43°01.1′	70°18.7′	140
540	43°01.3′	70°13.8′	170
541	43°01.3′	70°12.9′	170
543	43°01.4′	70°11.0′	169
544	43°01.5′	70°10.0′	170
552	43°01.7′	70°36.6′	37
554	43°01.7′	70°35.0′	34
556	43°01.7′	70°33.1′	49
558	43°01.7′	70°31.4′	70
560	43°01.8′	70°29.6′	84
562	43°02.1′	70°27.8′	93
564	43°02.2′	70°26.0′	93
566	43°02.3′	70°24.3′	100
569	43°02.5′	70°21.7′	116
572	43°02.7′	70°19.1′	143
573	43°02.7′	70°18.3′	137
575	43°02.8′	70°16.5′	158
577	43°02.9′	70°14.8′	158
580	43°03.1′	70°12.3′	171
585	43°03.4′	70°07.9′	158
587	43°03.5′	70°06.2′	142
590	43°03.6′	70°03.6′	96
591	43°04.3′	70°03.6′	96
592	43°04.3′	70°04.6′	105
595	43°04.2′	70°07.3′	160
598	43°04.1′	70°09.9′	168
600	43°04.0′	70°11.8′	167
601	43°03.3′	70°28.7′	78
602	43°03.4′	70°29.7′	46

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
604	43°03.6′	70°31.5′	51
606	43°03.8′	70°33.4′	40
607	43°04.0′	70°35.0′	27
610	43°04.6′	70°33.6′	37
614	43°04.7′	70°30.5′	56
618	43°04.8′	70°26.9′	77
621	43°04.9′	70°24.1′	90
623	43°04.9′	70°22.4′	82
625	43°05.0′	70°20.6′	111
626	43°05.0′	70°19.7′	120
629	43°05.1′	70°17.0′	140
632	43°05.2′	70°14.3′	152
634	43°05.2′	70°12.6′	152
642	43°05.4′	70°05.5′	119
644	43°05.5′	70°03.8′	100
645	43°07.2′	70°04.0′	116
647	43°07.1′	70°05.8′	139
648	43°07.0′	70°06.7′	142
649	43°07.0′	70°07.5′	150
653	43°06.9′	70°11.1′	168
654	43°06.8′	70°12.0′	181
656	43°06.8′	70°13.7′	152
658	43°06.7′	70°15.5′	145
660	43°06.6′	70°17.3′	126
662	43°06.5′	70°19.0′	125
663	43°06.5′	70°19.9′	118
664	43°06.5′	70°20.8′	111
665	43°06.4′	70°21.7′	102
666	43°06.4′	70°22.6′	92

Station	*N. Lat.*	*W. Long.*	*Depth in m.*
667	43°06.4′	70°23.5′	75
668	43°06.3′	70°24.4′	76
676	43°06.5′	70°28.9′	37
678	43°06.5′	70°27.2′	40
685	42°56.8′	70°07.3′	128
688	42°56.4′	70°09.7′	150
691	42°56.1′	70°12.2′	152
697	42°55.3′	70°16.9′	146
702	42°54.6′	70°21.1′	110
703	42°54.5′	70°21.9′	107
706	42°54.1′	70°24.3′	61
707	43°03.0′	70°36.4′	27
708	43°03.0′	70°34.5′	18
718	42°52.9′	70°23.1′	130
721	42°53.4′	70°20.3′	134
722	42°53.6′	70°19.4′	134
723	42°53.8′	70°18.5′	136
724	42°54.0′	70°17.6′	150
725	42°54.2′	70°16.7′	150
726	42°54.3′	70°15.6′	150
727	42°54.5′	70°14.7′	142
728	42°54.7′	70°13.8′	133
729	42°54.9′	70°12.9′	138
730	42°55.1′	70°12.0′	144
731	42°55.3′	70°11.2′	122
732	42°55.4′	70°10.2′	113
733	42°55.6′	70°09.3′	131
734	42°55.8′	70°08.4′	110
736	42°56.1′	70°06.6′	97
738	42°56.5′	70°04.7′	76

STATION	DEPTH IN METERS	TOTAL BENTHONIC POPULATION	BENTHONIC SPECIES IN %																														
			Ammodiscus ssp.	Bulimina aculeata	Cassidulina algida	C. norcrossi	Eggerella advena	Elphidium incertum var. clavatum	Eponides frigidus	Globobulimina auriculata	Glomospira gordialis	Haplophragmoides bradyi	H. glomeratum	Hormosina sp.	Hyperammina elongata	Labrospira crassimargo	L. jeffreysii	L. cf. nitida	Lagena	Nonion labradoricum	Proteonina atlantica	Quinqueloculina frigida	Recurvoides turbinatus	Reophax arctica	R. curtus	R. scottii	Spiroplectammina biformis	S. typica	Textularia torquata	Trochammina advena	T. quadriloba	T. squamata	Valvulina conica
2	110	364	6									8	42	3		7	4				15				13								
5	106	187	4								2	8	19			13	3				25		4	2	11		4		5	.5	2		
8	148	642	3									4	8			5	4				2		10	1	63		.5			.5			
14	129	517	1									24	28			10	8				3		14	6	17		4		1				
18	144	627	1								3	10	15		8	6	2				8		11	3	33	2	4		2	.2	.2		.2
21	172	724	3									41	14	2		18	1	6			3		7	3	10	3	.8						
22	162	1011	3				.3					10	7		.3	4	4				2		4	.9	58		5		2				
23	152	369	2									29	20	3		11	2	8			3		13	5	9	2	1				2	.8	.8
24	143	441	3				.7					21	11			19	2				10		9	.9	16	9	2		.9		.2	2	.2
25	143	400	7				.4				4	12	13			10	2				10		13		30		5	4	1	4	.4	.7	
27	104	1854	2			3	1				.1	22	16	6	1	12	2	.1			11		8	.3	15		2	1	1	1	.3	.6	.9
28	157	738	1				.5					3	23			14	3				6		22		7	1	13		7	.3	.4		.5
29	175	348	2									35	10			22	5				3		10	.9	5	6	5		2				.3
30	208	976	.8									8	20		4	13	3				12		13	.4	23		4		2		4		
31	160	454	1									3	17			8	2				4		11	.4	45		5		3				
33	122	440	6									3	9			13	3				7		7	1	44		.8		1				
34	95	231	1				2				4		32			3	2				7		3		12	.4	17		16			2	
35	104	225	2				3				4		17			15	2				1		4		4	2	16		32				
36	112	116	3										17			45	3				3				19		3		3				
40	116	138											14			24	13				4		8		12		7		15				
41	107	151											11			13	21				10		5		38		3						
42	108	302											25		.3	9	2		.3		10		.6	.3	38		7		5				
43	118	118	8									2	24	5		8	18				21				11		5		3				
48	95	374	.8									5	23		5	13	3				32		.5	.3	17	.5			2	.3			.3
50	100	108		17	20	7		4	2	20									4	20	4												
52	107	321	2									4	16			11	5				20		6	2	15		7		11	.3	.3	.9	
53	110	333	2								6	8	18	6	6	4	1	.3			14		7	.9	34		1	5					
54	119	888	2									8	14	7		10	2	.2			14		7	2	30		4		3	1	.2	.2	
55	125	488	2									13	19		1	5	2				11		11	1	26	1	3		2	.4	.2		.2
58	143	307	.7									6	20		3	9	3				9		7	.7	30	3	11		3		.3		.3
[illegible]1	158	737	2									13	21			13	3				14		1	.6	23	.6	4		2	.6		.4	
62	162	459		4						.9		62	11	2	4	6	3			.9	3		.4		8				4				
65	168	702	2				.9					20	12		9	9	4	6			5		8		31		2	.6	2	.3	.6		
67	172	1080	3				.4					6	13	4		10	4	.4			8		8	.7	35		6		3	.7		1	
68	171	660	3									15	15		1	13	1				8		11	.6	27		2		2	.9			.3
71	180	473	1				6				2	11	17		.4	15	2				20		10	.4	15		4		2	.2	2	.4	.2
73	183	185	1									37	8			6	6				10		10		19								
74	182	475	8									8	7	1		11	2				5		7	1	50	1	2		2	.4			
76	166	459	1				2					15	12	2	7	8	4				10		3	2	34	1	4		.9		.7		
80	152	879	2									16	25	3	.3	8	4				15		9	.7	10	3	4		2		.3		.3
82	146	743	6				.1					5	10		1	8	2				16		10	2	27	1	5		5	5	.4		.1
85	114	518	.8				8					.4	22			7	2				21		7		3		7	6	19		.4	.2	
88	100	384	.8				.8						12			8					9			2	20	3	16	.4	27				
90	93	252	4				3					4	2			4	3			.8	19		7	2	17	1	17	2	19				.4
91	66	107	3				3				2		14			8	.9				2		4	4	13	26	11		7			.9	
96	88	102	2				5						6			14					1			2	3	14	19		29			7	
97	94	5														80									20								
98	96	293	.7				1				.7		23		3	17	1				20		1	.3	21		6		7			.3	
102	117	428	.9										12			24	3				3		2	3	24		12		13			.2	
103	110	132											7			15	6				.8		1	.8	61		5		3		.8		
104	109	214					.5						16			29	3				4		.5	3	22		8	.5	13				
105	108	63											5			35					3		3	6	30		11		2				
106	107	193	1										18			42	.5				7		1	.5	14		9		5			1	
107	105	558	1				4						16			6	6				11		.7	2	25		11	2	18				
110	99	138	.7				1						16			16					6	.7	.7	4	24	6	7	2	13			.7	
111	98	446	2				4						18		.4	6	2				23	.4	3	2	17		10		14				
112	96	313	1				3				.3	.3	14		3	7	1				22	.3	3		11		17		18				
113	94	660	1				2					3	27			15	2				17		1	1	16		7	6	8			.3	
114	93	507	.8				2						18		.2	8	1				25		1	2	9	3	6		20		.2	3	

Table 2. Occurrences of Foraminifera species at stations 2–114

STATION	116	118	121	123	128	131	132	133	134	135	136	137	138	139	141	142	143	144
DEPTH IN METERS	87	90	89	90	76	73	74	73	76	75	73	73	70	69	67	65	64	61
TOTAL BENTHONIC POPULATION	408	33	96	66	162	516	112	622	199	177	161	174	171	159	312	248	317	246
BENTHONIC SPECIES IN %																		
Ammobaculites cassis														.6		.8	3	5
Ammodiscus ssp.	3	6	2	3	.6	3		6	.5	2		6	6	1	.9	.4	3	
Eggerella advena	4	9	2		9	6	23	3	12	4	6	11	13	13	25	32	29	42
Glomospira gordialis						2											3	.8
Haplophragmoides bradyi																		
H. glomeratum	30		9	3	4	.8	5	.2	1	2	5	6	3	4	2	3	6	2
Hippocrepina indivisa								.3	3	.6					3	4		.4
Hyperammina elongata	5																	.8
Labrospira crassimargo	4	6	7	20	7	.2	2	.3	4	1	6	3	5	6	1	6	5	.8
L. jeffreysii	1		2	1														
Proteonina atlantica	11		1		2				2		.6		2	4	1	4	6	8
Quinqueloculina frigida																		
Recurvoides turbinatus	1			1	2	2	9		2		2		3		.3	3	1	4
Reophax arctica			5	3	3	2	2	1	1	4	2	3	2	1	3		1	8
R. curtus	7	18	22	14	2	1	2	6	4	1	8	2	11	4	4	11	3	7
R. scottii	1	15	12	12	19	49	17	64	43	33	25	16	29	29	21	4	8	11
Spiroplectammina biformis	16	6	14	15	19	9	20	3	9	12	15	20	18	6	8	16	14	9
S. typica	1					.2				1	4	1					1	
Textularia torquata	16	15	5	12	16	16	18	11	8	27	15	15	6	19	25	15	17	10
Trochammina lobata						2		2						.6				1
T. squamata	2	15	18	9	17	12	9	14	8	11	11	22	6	11	7	3	4	2

STATION	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165
DEPTH IN METERS	74	76	76	78	81	80	82	85	82	82	79	76	72	64	67	73	81	86
TOTAL BENTHONIC POPULATION	77	52	94	76	94	46	46	53	67	118	168	365	336	210	139	127	80	119
BENTHONIC SPECIES IN %																		
Ammobaculites cassis												.3	.3					
Ammodiscus ssp.	3	2	1	1	2	4	2	4	3	3		.3	6	11	3	10	5	
Eggerella advena	13	2	2	4	6	4		2	6	10	5	14	21	35	32	4	1	
Glomospira gordialis			1										.6			.8		
Haplophragmoides bradyi																		
H. glomeratum	3	8	6	3	4	13	15	6	4	.8	2	.8	2	.5		5	9	8
Hippocrepina indivisa																8		
Hyperammina elongata													3					
Labrospira crassimargo	1		8	4	6	4	6	6	7	5	2	2	2		4	3	18	15
L. jeffreysii									1									2
Proteonina atlantica				11	4	9		4	1			.3	2		7		4	.8
Quinqueloculina frigida																		
Recurvoides turbinatus	1		2		1		4	4		8		3	3		7	2	2	2
Reophax arctica	3	6	11	4	1	13	6	7			10	5	1	5	4	5	4	4
R. curtus	4	10	11	12	3	4	20	13	6	6	3	2	19	1	4	8	12	27
R. scottii	20	12	10	20	6			9	24	32	42	52	10	15	19	19	8	13
Spiroplectammina biformis	23	15	19	16	30	22	22	23	24	22	8	10	14	14	11	13	18	13
S. typica			1					2				1	6	1	7			
Textularia torquata	16	17	22	22	22	22	15	15	7	9	10	11	13	11	13	20	14	12
Trochammina lobata														.5				
T. squamata	8	27	8	14	13	4	9	6	15	10	16	5	5	10	7	10	6	2

STATION	166	167	168	169	170	173	175	176	178	181	182	183	184	185	186	190	192	194
DEPTH IN METERS	88	92	100	98	96	87	80	64	73	90	98	92	92	92	99	92	86	76
TOTAL BENTHONIC POPULATION	82	84	52	149	171	115	294	137	136	171	98	134	168	88	129	155	87	95
BENTHONIC SPECIES IN %																		
Ammobaculites cassis																		
Ammodiscus ssp.		1		1	2	2	7	7			1		6	2	3	.6	3	
Eggerella advena			2			.8	5	20	6	2		.7		2			2	6
Glomospira gordialis							2	.7										1
Haplophragmoides bradyi						.8												
H. glomeratum	9	5	10	8	8	13	7	20	11	12	18	19	11		19	10	14	3
Hippocrepina indivisa																		
Hyperammina elongata																		
Labrospira crassimargo	23	13	19	37	14	3	5	9	6	8	10	7	8	11	18	23	14	10
L. jeffreysii			4	2		8	7	7		6	1		2		2	6	1	
Proteonina atlantica	1		15	4	2	3	2	12	14	19	6	7	2	2	2	2		1
Quinqueloculina frigida	1													1				
Recurvoides turbinatus	1	1	4	7	3		.7	.7		3	4		4	1	2	6	1	
Reophax arctica	1	5	4	7	5	3	2		7	6	7	4	2	1	4	4	3	
R. curtus	19	20	16	20	26	13	10	3	29	20	8	29	48	43	31	25	12	7
R. scottii	5	11	10			7	8	1	10	7		1	2	2				22
Spiroplectammina biformis	15	21	12	10	16	21	16	6	12	8	15	21	9	12	11	17	17	4
S. typica					6	3	3				2	.7					2	
Textularia torquata	17	20	6	9	19	30	26	22	10	17	21	14	11	20	7	13	7	7
Trochammina lobata																		
T. squamata	7	1		.7	3	.8	7	3	1	5	5	1	2			3	23	35

Table 3. Occurrences of Foraminifera species at stations 116–194

STATION	196	197	201	203	205	207	213	215	219	221	222	223	224	226	228	230	231	234	236	239	242	243	246	247	248	249	250	253	254	255	256	259	261	263	265	270	271	273	274	275	277	284	287	310	312	314	315	317	319	320	322	334	335	336	337
DEPTH IN METERS	67	46	64	89	84	150	109	100	85	78	70	49	58	82	87	99	100	122	122	131	59	64	65	73	70	111	132	143	145	148	152	174	174	174	174	51	67	88	100	110	127	171	162	43	41	40	31	26	13	34	37	38	41	43	43
TOTAL BENTHONIC POPULATION	378	7392	586	453	184	81	454	253	813	332	429	999	4569	1568	414	486	335	656	251	490	1066	3000	3744	2816	5680	2184	393	567	622	578	1125	1212	1288	423	669	198	3488	520	5520	2200	1260	1028	566	367	124	94	614	3080	336	546	522	1023	4392	3424	4640
BENTHONIC SPECIES IN %																																																							
Ammobaculites cassis	5				5	1			.4																																							1							
Ammodiscus ssp.			5	1	2	5	4	3	1	6	7	1		.8	2	1	1	2	8	8	4		9	3	6	.7	8	8	1	7	3	2	2	3	1	1		8	3	2	2	2	1	.8	8		.6	4	6	7	3	3	.9	.2	.3
Angulogerina angulosa		7										1	1	2							2	2	.9	2	2	4			3									8	1	1	2											4		.2	
Astrononion stellatum		2										5	2	.5							2	4	3	9	3	2										1		4	5	3	2			.5		1		2			4	3		.5	
Bulimina aculeata																						3							1										2	1	2											1			
Cassidulina algida		20										4	30	2							10	9	19	3	4	2			.3							44	79	48	8	10	3			2	2		5	4	.6	.7	8	3	2	3	6
C. islandica var. minuta		1											.6												.3															.2					2							.9		3	7
C. norcrossi																					.9		.4	.3																	.3							.1							
Cibicides lobatulus		21										3	45	9							7	38	38	5	33	.4										41	13	10	3	6	2			2	6		22	9	3		1	12	5	10	12
Discorbis columbiensis																																													2				6			5		7	1
Eggerella advena	6	9	1	1	1				7	6	2	17	4	17	3	1	3	3	4	1	12	5	6	11	4	2				.3		.3	2			3		5	4	3	2			60	52	85	20	53	60	62	60	42	54	31	26
Elphidium articulatum		1												3												.4												2						3				3	6	1		3	2	6	4
E. incertum var. clavatum		13										1	2								3		9	3														.8						2	2		7	6	7	1	4	3	9	4	6
E. subarcticum		9										1	4	5							2	2	1	2	.8											3	4	8	4	7	1			8	16	1	23	10	11	10	5	6	4	7	9
Eponides frigidus		8										4	6	2							6	12	7	5	1	3										2	.2	1		5	5			4	3	1	3	1	1	3	.8	7	6	9	9
Globobulimina auriculata		8										.6									8	2	4	3	3	1			2										1	9	2											1			1
Glomospira gordialis						1							1	3										3	3					3			2							7														2	
Haplophragmoides bradyi									4						2		2	3	1	4				3	3	4		6	5	6	17	9	2	17	13				9	1	3	15	6												
H. glomeratum	15	1	23	19	28	20	11	11	24	17	29	24	3	26	20	23	18	37	13	17	18	9	7	35	21	39	24	21	23	27	13	19	17	18	18	5	2	4	31	26	32	26	15	5				1				4	4		
Hyperammina elongata					2		4		.4	3	7				5	3	9	3	2	4								8	3	7					9							4													
Labrospira crassimargo	5	.5	13	8	13	7	17	16	8	16	9	5		4	8	8	10	6	20	8	2	1	6	8	6	3	14	9	9	8	11	8	7	17	8	5	7	10	2	5	2	7	7	3	8			1		4	4	1	1	7	2
L. jeffreysii			2	2	1	1	5	9	4	9	1	2		3	2	1	5	3	9	7	8	2	1	3	3	1	2	3	2	3	3	3	2	5	2	5	.5	8	1	3	1	3	6						9						
Lagena		1										7	2								1	1	9	1	3	7										1	5		.9	7	3							1	6		8	6	7	2	1
Miliammina fusca																																												.5			3		3						
Nonion labradoricum		1										3	3	.3							2	1	1			1			3										2	2	3														3
Patellina corrugata		2																				2			3																														
Proteonina atlantica	7	1	12	18	10	6	6	5	16	16	26	12	3	21	23	16	32	19	17	11	17	2	2	10	5	12	13	12	22	23	10	8	7	15	15		2	15	13	12	9	8	8	16	5	5	14	16		16	13	12	11	10	8
Pseudopolymorphina novangliae																							4																					3			6		3						
Quinqueloculina frigida	1		3						7		2				2		.3																															1							3
Q. seminula																						2				4			3												.3								9		8				
Recurvoides turbinatus	2	.2	2	1	1	1	1	8	3	1	4	4		2	5	.9		4	2	3		.5		6	4	6	10	16	11	9	9	11	10	8	13				1	7	3	13	24									1		2	
Reophax arctica	3		1	3		1	2	3	2						2	1	2	1		8		2					1	2		7	1	8	6	5	2						1	1	2									1	2		
R. curtus	14	2	5	19	18	16	38	33	15	22	15	2			7	4	6	10	25	30	9			6	6	7	9	9	9	6	28	29	37	10	6				1	1	.6	16	20	.8			6			4	4	2	4	2	
R. scottii	21	1	4	11					1	1		2	3	3	1	2	6	9	2	4					3		3	5		3	8	5			4						.3	6										2	1	2	2
Spiroplectammina biformis	13	8	9	9	9	15	9	9	13	7	5	3		3	5	9	9	7	4	8	3	3		1	8	5	7	6	2	7	3	4	9	5	7				4	3	5	2	6	2	8		3	9				2	2	2	7
S. typica		2	1					8	4		7	1		1		3		2		2	2	.3		1	.3	4			4	3								4	2	2	2	2		3		3					1	1	7	2	1
Textularia torquata	11	3	11	11	10	20	8	11	11	15	4	9		3	25	20	13	6	5	6	2	2	4	1	2	11	14	8		5	5	5	4	.2	7				2	1	7	5	4					1		4	8		9	7	1
Trochammina advena							4											6								4	3	8	3				2		.4				.9	4	.6														
T. quadriloba				.3								.1																5		3	.3	8	2	7						4	.6														
T. squamata	3	7	1	1	2	5	.4		.4	2	7		■	2	7	3		.6	4	■	.4	2			8	4	1		.3				8	2	.9				1	5	1	2		3	8	1	3	3			4	.3	.5	7	3
Valvulina conica																		.3		4			.4			1			1	3					.4				2	2	.6														
Virgulina complanata																						.3																	2	1	2														
V. fusiformis		4										.5	3	1							2	2	.9	1	2	1												.4	7	5	1			3	8		1	5	3	7	2	7	1	6	2

Table 4. Occurrences of Foraminifera species at stations 196–337

STATION	338	339	340	342	350	353	354	355	356	363	372	374	376	378	380	382	383	384	385	386
DEPTH IN METERS	42	50	56	34	30	32	32	30	29	21	21	27	27	31	34	37	37	35	36	35
TOTAL BENTHONIC POPULATION	1056	5248	5920	3336	4336	3723	3344	1000	1686	99	417	292	6	244	2064	1280	1118	15144	1676	81
BENTHONIC SPECIES IN %																				
Ammobaculites cassis		.6								1								.6		
Ammodiscus ssp.	.4		5	5	7		1	2	13	8	3	1		4	4	4	2	.3	5	
Angulogerina angulosa	4		5					.4											.7	
Astrononion stellatum		3	1			3	2				2							.2		
Bolivina pseudo-plicata				2	7	3	2				2									
Buliminella elegantissima				7		.2					2	3		4						
Cassidulina algida	8	2	10	6	10	9	2	3	1	1	1	1		8	3	6	3	.2	6	
C. islandica var. minuta	.8		.5	1	7	.5	.7	1	9		2	3		.4		.3				
Cibicides lobatulus	10	3	7	24	17	27	9		1	1	3	.7	17		9	19	17	.6	9	85
Discorbis columbiensis	2			.2	4		2	.8			2	3								6
Eggerella advena	27	46	38	19	18	16	50	51	41	22	36	49		67	36	25	43	57	54	4
Elphidium articulatum	1	1	1	1	2	.9	.7		2	3	2	.3				.3	3	2	1	
E. incertum var. clavatum	8	3	4	12	17	16	5	7	2	20	8	3		2	1	3	2	8	4	2
E. subarcticum	5	2	4	8	8	9	7	8	11	18	17	22	33	3	17	8	33	1	5	
Eponides frigidus	12	7	8	10	4	3	8	8	2	1	2	2		3	1	1	4	6	6	
Globobulimina auriculata		.3	1				.1											2		
Haplophragmoides bradyi																				
H. glomeratum			2												.8				.5	
Hippocrepina indivisa																				
Labrospira crassimargo	.8	.6	3	.7			1								.4	.3		.3		
L. jeffreysii																				
Lagena	1	[illegible]	.5	1	.7	3	.6	.8	.7					.4		.3			5	
Miliammina fusca									8											
Miliolids				2	.4		2	8	.8		.7			.8						
Nonion labradoricum	.4	3				.2														
Polymorphinidae				2			.1			1							.2			
Proteonina atlantica	11	22	7	7	7	4	8	1	3	23	9	14		18	4	11	11	21	9	
Pseudopolymorphina novangliae					.4						.2	.7				.3			.2	
Quinqueloculina arctica	.4			.5		.2			.1							.3				1
Q. frigida				2			1					3				.6				
Q. seminula					.4	2		.4	1		1	1							.5	
Q. subrotunda				.2	.4			.4	5						.4			.3		
Recurvoides turbinatus																				
Reophax arctica					.4				.1									.2		
R. curtus	.8	.6	1	1			.6		.1						1	6	.9	3		
R. scottii	.8	.9	.5	.2	4	1			3		3	1		.8	2	.3		.5		
Spiroplectammina biformis	1	.9	4	.5		.7	1	.8	2		.2			.4	8	.3	7	4	.2	
S. typica	.8		5	5	.4	2	.5		1		.2	3		.8				.5	.2	
Textularia torquata	.4	.6	2	.7		.7	2	4	2		.2				4		1	1		
Trochammina advena																				
T. lobata	3	.9		1		.3	.1				2	1		4		.3	4	4	2	
T. squamata	4	2	3	.5	4	3	.4		9		3	1	50	1	13	16	4	1		1
Virgulina fusiformis	2	3	2	1	2	6	1	2	1		3					.3	1	1	.2	

STATION	388	389	390	391	392	393	395	397	402	404	406	408	410	420	439	451	453
DEPTH IN METERS	35	35	37	36	28	26	21	20	22	20	17	12	9	11	23	25	20
TOTAL BENTHONIC POPULATION	37	10880	2440	1684	195	546	1344	1136	102	3332	844	208	58	105	13440	10	19840
BENTHONIC SPECIES IN %																	
Ammobaculites cassis			.3														
Ammodiscus ssp.			.3	.5	1	3		4	12	2		1			2		.3
Angulogerina angulosa		1		.7													
Astrononion stellatum				2			4			1	.2						
Bolivina pseudo-plicata							.1	4		.5		.5					
Buliminella elegantissima							1										
Cassidulina algida	11	13	6	4	3	4	2	2			1		2		15		4
C. islandica var. minuta			.7			1				1	.5						
Cibicides lobatulus	76	15	17	5	23	34	8	58	14	5	5	8	3	63	31	90	79
Discorbis columbiensis			1		5	4	1		1	1	2						3
Eggerella advena	5	24	24	30	26	16	42	5	17	52	11	38	40	8	4		2
Elphidium articulatum			1	4	2	3	14			4					2		
E. incertum var. clavatum	5	14	6	5	15	16	9	22	11	23	48	20	22	13	23		5
E. subarcticum	3	4	8	7	9	14	1	3	20	5	29	14	24	1	14		6
Eponides frigidus		13	9	9	6	2	7	4		2	2	4			3		1
Globobulimina auriculata																	
Haplophragmoides bradyi																	
H. glomeratum								2									
Hippocrepina indivisa																	
Labrospira crassimargo			3		.6		6	7			.2					10	
L. jeffreysii																	
Lagena			[illegible]	7	1	4	.9			2	2				1		3
Miliammina fusca									2	.5	.5						
Miliolids					2		.4	.4	12					4	4		.3
Nonion labradoricum																	
Polymorphinidae															.2		.3
Proteonina atlantica		13	12	24	2	5	8	3	1	4	2	1	3		2		.3
Pseudopolymorphina novangliae		.6	.3			.4	6								.2		
Quinqueloculina arctica				.5										6	.2		.3
Q. frigida			.7									.5					
Q. seminula					6				1			.5		6			
Q. subrotunda						.7											
Recurvoides turbinatus				2													
Reophax arctica																	
R. curtus				1				.4									
R. scottii			3	1								2			.5		.3
Spiroplectammina biformis			1	.2			.3										
S. typica		2	.3	.5								.5					
Textularia torquata			.7	.5			.1			.1		.5					
Trochammina advena																	
T. lobata			1	4	[illegible]	4	2	1				.5	2				
T. squamata							1		6	.7		2			.5		
Virgulina fusiformis			2	.5	6		.1	.4	4			4			2		.3

STATION	466	472	474	478	480	482	486	494	496	506	507	508	512	516	520	521	522	523
DEPTH IN METERS	56	38	58	87	73	97	118	144	152	148	137	128	100	88	59	69	79	84
TOTAL BENTHONIC POPULATION	5280	455	363	294	640	578	418	390	565	1104	760	701	1014	4360	332	252	311	183
BENTHONIC SPECIES IN %																		
Ammobaculites cassis	3		1	.7											.3	.8		
Ammodiscus ssp.			3		2	3	5	2	1	1	2	2	1		1		6	1
Angulogerina angulosa	6	4												.2				
Astrononion stellatum	3	1												2				
Bolivina pseudo-plicata																		
Buliminella elegantissima																		
Cassidulina algida	3	20												2				
C. islandica var. minuta	6	7																
Cibicides lobatulus	9	36												.4				
Discorbis columbiensis					2													
Eggerella advena	30	1	24		2	.3			7				.3	3	24	21	5	4
Elphidium articulatum	.6	.7												.2				
E. incertum var. clavatum	4	11												.6				
E. subarcticum	10	9												.2				
Eponides frigidus	6	3												5				
Globobulimina auriculata	.3	2		7	.8		1							16				
Haplophragmoides bradyi								1	16	5	6	7						
H. glomeratum	3		5	14	22	23	32	31	23	16	19	20	29	18	3	10	12	6
Hippocrepina indivisa			1			.3									.3		.3	
Labrospira crassimargo	4	2	3	9	12	18	6	10	9	10	21	16	5	4	3	4	5	6
L. jeffreysii			3	3	5	2	7	3	3	1	2	2	3	.7	1	.4	6	.5
Lagena	1	1												4				
Miliammina fusca																		
Miliolids																		
Nonion labradoricum	6	.2			.3		.5							15				
Polymorphinidae																		
Proteonina atlantica	17	3	7	41	29	9	17	22	17	14	19	29	24	22	10	13	11	1
Pseudopolymorphina novangliae		.9																
Quinqueloculina arctica	.3	.4																
Q. frigida		.4	.6															
Q. seminula																		
Q. subrotunda		1																
Recurvoides turbinatus	.3		.3	3	2	8	2	8	9	12	5	2	3		.6	2	1	1
Reophax arctica					.9	1	2	1	.7	3	7	.9	2		.3		5	2
R. curtus	.3		9	8	4	19	4	7	8	31	18	8	6	4	15	9	4	11
R. scottii	.3		22	7	.8	1	5	1	1		.4	2	2	.7	4	4	19	33
Spiroplectammina biformis	2	.2	14	2	7	7	12	8	5	3	4	6	11	2	12	9	12	11
S. typica					.3		.5								4	2	1	2
Textularia torquata	2	.2	8	10	17	9	13	5	4	3	3	3	12	3	19	16	16	16
Trochammina advena						.3	.5		5	.3			.6					
T. lobata	2	.4																
T. squamata	.6	2	4		.5	1			1				.6	.6	2	7	8	4
Virgulina fusiformis	1	4												1				

Table 5. Occurrences of Foraminifera species at stations 338–523

STATION	525	526	528	529	530	531	533	534	535	540	541	543	544	552	554	556	558	560	562	564	566	569	572	573	575	577	580	585	587	590	591	592	595	598	600	601	602	604	606	607	610	614	618	621	623	625	626	629	632	634	642	644	645	647	648
DEPTH IN METERS	85	97	96	105	110	113	128	134	140	170	170	169	170	37	34	49	70	84	93	93	100	116	143	137	158	158	171	158	142	96	96	105	160	168	167	78	46	51	40	27	37	56	77	90	82	111	120	140	152	152	119	100	116	139	142
TOTAL BENTHONIC POPULATION	290	247	287	717	541	775	483	578	505	262	885	442	565	372	218	11040	3056	1400	225	322	654	774	291	632	1263	544	330	717	701	2008	203	7420	452	690	1569	314	304	3642	5648	42	10400	1176	864	1251	924	972	466	1059	706	1318	2915	1092	1498	2284	281
BENTHONIC SPECIES IN %																																																								
Ammodiscus ssp.	.3	1	1	.4	.2	3	1	2	2	.4	1	3	3	.3		.3	.3	.3	2		.3	2	.7	2	2	3	1	1	.7	1	1	1	3	3	2	2	1	.2			.5		2	.2		.1	1	.8	2	2	.7	.4	.4	1	1
Angulogerina angulosa																	.6	.3	.3													.4		.5						.2	.3													.2			1	
Astrononion stellatum																	6	2														.4		2						.2	.9		.5											1			3	
Cassidulina algida															17	6	23	4	5													62	45	38						6	12	5	6	20											32	59	70	16	
C. islandica var. minuta																5		5	1																							.3			2															.2	
Cibicides lobatulus															51	40	22	9														14	40	11						7	22	74	18	42											10	33	17	12	
Crithionina pisam var. hispida						.2							.3																											.9																							
Eggerella advena	3	2	.3	.4						.4		.9	.7	1	5	12	1	7	.4		.6					.7		2	.7	6	2	3		.6	1	7	21	32	20	5	23	8	5	2							6	.4	1	6	4
Elphidium articulatum															.5		6	.3	.6															.5								.3	.3		7	1															
E. incertum var. clavatum															15	31	7	3	.3																							2	9	9	13	10											.2		.1	.2	
E. subarcticum															7	5	6	3	3													3	6	3						3	11			5											.9	3	3	.7	
Eponides frigidus															3	5	7	2	4													2	1	1						5	6		5	6											2	1	1	9	
Globobulimina auriculata																	.6	4	11																.3						2	.3		.2	.3												.1	.7	
Glomospira gordialis														.2					.3													.6									.3																			.1	.2	.4
Haplophragmoides bradyi			.3	.7	.7	1	4	6	4	5	4	4	13								.3	2	6	3	9	10	6	9	8			.3	7	4	23											.3	.5	16	5	10	5					3
H. glomeratum	19	17	29	23	15	21	27	21	24	32	16	9	15			2	12	21	6	23	20	18	25	27	20	19	28	18	22			12	16	16	12	11	9	3	.1				9	17	28	31	18	27	27	10	15		.4	23	23
Hyperammina elongata			.3	.6	1			1	.4				1								.5		.1			.5	.7			.4				.4	.3															.3	.6	.3		.2					.4
Labrospira crassimargo	8	3	9	10	13	8	9	5	10	8	5	5	6		2	1	5	4	7	8	9	10	6	6	6	3	8	12	11	6		5	4	6	11	9	2	1	1		2	2	3	8	8	13	12	10	9	9	2	1	3	3	4
L. jeffreysii	.7	.4	2	2	7	5	3	4	3	3	4	4	3				.5	.6	1	1	.6	5	1	3	3	3	2	2	3		2	.8	8	2	4	.6	.3							.7	4	.6	.6	1	2	4	2	.3		.1	2	6
Lagena															.5	1	2	.3	.3													.4	.5	1						2	1	2	2											.7		.1	1	
Miliolids																		.3	.5																.5							.1	2	2														.2	
Nonion labradoricum																		.6	3	12																						2	.3		.2											.2			2	
Proteonina atlantica	7	6	33	30	22	20	22	15	18	17	6	6	6	2	2	7	14	7	3	15	31	17	27	15	10	6	7	10	12	3	.5	14	12	8	8	1	6	11	3		5	.7	2	6	30	37	25	23	11	7	20	2	1	7	16
Quinqueloculina frigida			.3		.6																	.6																						.5															
Recurvoides turbinatus	2	1	3	2	.6	6	4	12	6	4	14	9	6				.3	3		2	2	1	7	1	9	14	15	10	10	12			.8	8	19	10	3	1	.5			.2		1	4	.3	.6	2	8	14	26	1			4	2
Reophax arctica	2	4	.7	.1	.4	2	1	2	2	.4	1	2	.2					.9	3	1	1	2	1	2	.2	1		.4	1				2	.3	1	.3	1	.2					1	.5				.3	1	.2					.4
R. curtus	20	20	10	8	20	12	9	12	20	6	25	48	16				.6	4	2	38	25	8	8	9	14	29	20	22	23	9			.8	26	30	19	13	5	.4	.1		.4		7	16	1	3	3	12	8	30	.4	.4		.9	8
R. scottii	8	8		.6	1						2				.9		7		15	5	1	3	6	2	.7	2	.6	2	3				2		.6	17	14	2	3		.7		35	15					.3	.8					3
Spiroplectammina biformis	9	18	4	12	7	10	9	7	6	9	12	5	22		.5	2	9	10	10	6	13	10	8	8	4	7	8	5	4				6	7	4	10	16	7	2		2	1	17	17	6	4	7	4	8	3	3			1	5
S. typica	.3	.8	.7	.4												.3	.5			.5								.4									.3		1						.7	.7	.6	.3					.2			.9	
Textularia torquata	19	18	5	11	9	9	9	9	4	3	8	2	.7	.5		.3	9	7	12	9	10	15	6	5	1	5	3	3	5			.5	4	1	2	21	18	7			.7		11	10	6	8	11	4	4	2	2			.9	11
Trochammina advena			.3	.1		.6	6	7	6	3	1										.3	.1	1		.5	2	3		.3			.5	.4	.3	.2										.3	.2	.4	.3	1	.5				.4	.4
T. lobata															.3																		.8						.2	.1																.4	
T. quadriloba							1		.7	.4	1	1		2				.3						.5			.2	.4			.4					.3	.2	.3									.3	.1	.9	.6		.3					
T. squamata	3	1							.3		.4	.3	.9	1	.3		.6	2	1		2		.1		2		.4	.3	2	6	1	.5		.9	.6		2	5	.5	1		1	.3	5	1	16			.3			9		.8	.2	13
Valvulina conica			.3						.2	5			.2											.7							.4																				.2	.3	.3				.4	
Virgulina fusiformis															.5		3	2	9														4		1						2	5		5											.2			.9	

Table 6. Occurrences of Foraminifera species at stations 525–648

STATION	649	653	654	656	658	660	662	663	664	665	666	667	668	676	678	685	688	691	697
DEPTH IN METERS	150	168	181	152	145	126	125	118	111	102	92	75	76	37	40	128	150	152	146
TOTAL BENTHONIC POPULATION	515	284	465	353	688	1120	583	720	583	312	327	406	61184	186	558	5360	424	873	397
BENTHONIC SPECIES IN %																			
Ammodiscus ssp.	2	1	2	6	1	9	9	2	9	3		.2	6	5	4	4	9	1	4
Angulogerina angulosa													4	2		2			
Astrononion stellatum													2			.9			
Bolivina pseudo-plicata																			
B. subaenariensis																.1			
Bulimina aculeata																1			
Cassidulina algida													6	24	17	4			
C. islandica var. minuta																1			
C. norcrossi																4			
Cibicides lobatulus													1	29	76	2			
Eggerella advena	1		2	3							6	1	10	26	4	6	5		2
Elphidium articulatum													1		6				
E. incertum var. clavatum													2	4	5	1			
E. subarcticum													2	2	3	.9			
Eponides frigidus													6	3	2	5			
E. wrightii															7				
Globobulimina *auriculata													1			6			
Glomospira gordialis	2		4					8					.2						
Haplophragmoides bradyi	4	4	3	16	20	5	1	6	3	3	3		2			2	6	4	8
H. glomeratum	15	23	19	25	15	26	23	23	21	30	20	18	38	4		37	22	18	15
Hormosina sp.					.3														
Hyperammina elongata	.4	.4	8	1	1	4		.3									5		3
Labrospira crassimargo	13	7	15	10	11	1	12	9	7	4	4	6	8	1	1	2	24	17	18
L. jeffreysii	3	3	3	1	3	1	4	3	5	4	3	2	8	1		2	1	2	3
L. cf. nitida	.2																		
Lagena													2		7	9			
Miliammina fusca															.7				
Miliolids													4			3			
Nonion labradoricum													2			2			
Proteonina atlantica	12	5	17	27	21	15	21	15	27	17	20	15	17		1	11	7	17	13
Quinqueloculina frigida												2			.4				
Q. seminula															.4				
Q. subrotunda																			
Recurvoides turbinatus	6	11	16	7	5	6	6	6	3	1	3	1	2	2	.7	6	3	15	5
Reophax arctica	3	2	1	.3	6	2	2	2	1	1	4	2	2				1	2	1
R. curtus	12	12	12	4	10	10	7	21	12	5	5	14	2		2	.3	9	11	20
R. scottii	5	2	1		6	.2	.7			3	10	10					4	7	
Robertina cf. charlottensis																.3			
Spiroplectammina biformis	8	12	6	3	3	8	8	9	11	12	13	8	3	5		6	10	8	8
S. typica													6			1	.9		
Textularia torquata	10	4	2	1	4	10	12	8	10	17	15	15	3			7	5	2	2
Triloculina tricarinata																			
Trochammina advena	.2	.4	.4	2	2	2	.2		1	6	6					4		3	.5
T. lobata														.5		4			
T. quadriloba	.4	4			.4	2	.2	.3	.2				2			3		7	
T. squamata	4	3								4	3	6			12	1	3	1	
Valvulina conica	8	1		2	1	2										1	.5		
Virgulina complanata												.2			1				1
V. fusiformis												1			6				

STATION	702	703	706	707	708	718	721	722	723	724	725	726	727	728	729	730	731	732	733	734	736	738
DEPTH IN METERS	110	107	61	27	18	130	134	134	136	150	150	150	142	133	138	144	122	113	131	110	97	76
TOTAL BENTHONIC POPULATION	2120	280	5180	2840	28544	1372	4430	284	340	770	828	676	177	714	510	762	263	337	495	283	1000	552
BENTHONIC SPECIES IN %																						
Ammodiscus ssp.		1		.3		6	5	1	3	3	2	3	1	.8		1	2	[illegible]	2	1	.8	
Angulogerina angulosa	.4		2			3	2															
Astrononion stellatum	1		.2			3	2															
Bolivina pseudo-plicata				3																		
B. subaenariensis																						
Bulimina aculeata	4						1															
Cassidulina algida	4	.7	1	2	14	2	4														2	28
C. islandica var. minuta	4																				.4	
C. norcrossi							5															
Cibicides lobatulus	3	1	2	66	73	2	1														14	66
Eggerella advena	1	4	9	8	9	9	2	.4		.1							4		4	3	4	
Elphidium articulatum				.3	.4	1																
E. incertum var. clavatum	.8		2	3	7	6	5															
E. subarcticum	2		.4	2	2																.8	.7
Eponides frigidus	6		2	.6		3	4														4	1
E. wrightii																						
Globobulimina *auriculata	7	4	4			3	16													.4	2	
Glomospira gordialis			1						5				.6					.3		.4		
Haplophragmoides bradyi	8		.4			.6		2	2	1	4	4	9	13	3	9	3	9	7	5		
H. glomeratum	27	24	34	.3		35	19	11	16	9	13	17	14	22	25	19	29	24	27	41	34	2
Hormosina sp.										.4												
Hyperammina elongata								.4		.4		.3	1	1						.4		
Labrospira crassimargo	1	9	3	3		5	2	23	25	4	9	5	12	15	9	14	18	16	16	5	2	.4
L. jeffreysii	1	3	2			.6	.2	12	4	2	5	2	2	.6	4	3	1	1	1	2	.8	2
L. cf. nitida											4											
Lagena	.8		.4	.6	4	.3	.7														2	.4
Miliammina fusca																						
Miliolids	1			.8	8		.9														.8	
Nonion labradoricum	.2	3	.8			5	19															
Proteonina atlantica	8	25	21	.3	.4	22	18	8	8	6	7	9	34	26	29	18	26	.3	27	12	6	
Quinqueloculina frigida											.2											
Q. seminula																						
Q. subrotunda	.4			14																		
Recurvoides turbinatus	4		4			1	1	7	9	6	11	15	9	10	11	9	7	4	5	7	2	
Reophax arctica	.4	.4						1	2	2	1	2	6		4	5		1	.2			
R. curtus	8	11	1			3	.7	21	16	53	37	28	11	6	3	18	5	1	4	1		
R. scottii				8							4							3				
Robertina cf. charlottensis		.4	.2																		.4	
Spiroplectammina biformis	5	11	3		.4	3	1	9	8	7	5	6	2	2	7	3	4	16	5	5	3	
S. typica	3	.7	3			3	1	7	6	1	.4	.3							.8	1	7	
Textularia torquata	5	5	6	.3	.4	2	.9	4	3	6	3	7	.6	1	7	3	1	17	1	12	2	
Triloculina tricarinata																						
Trochammina advena		2					.2			.4	.4		2	.3	2	.3	2					
T. lobata						.6																
T. quadriloba			.4					.4	2	1	.2		1	3				1	1	1		
T. squamata	8			3			.2		.3		.4	6		.3		.5		1		1	1	
Valvulina conica			.4			1			.3			.3	.6	1		1	2	.3	.6	1		
Virgulina complanata		.2			.6	.9															.4	
V. fusiformis			.6			.5															2	

Table 7. Occurrences of Foraminifera species at stations 649–738

STATION	2	5	8	14	18	21	22	23	25	27	28	29	30	31	33	34	41	42
DEPTH IN METERS	110	106	148	129	144	172	162	152	143	104	157	175	208	160	122	95	107	108
TOTAL LIVING BENTHONIC POPULATION	22	2	72	14	62	14	90	57	63	146	79	12	68	82	316	20	35	45
BENTHONIC SPECIES IN %																		
Ammodiscus ssp				7				3		1	1							2
Cassidulina norcrossi										4								
Crithionina pisam var. hispida																		
Eggerella advena																		
Haplophragmoides bradyi			4	7			3	63		19					1			
H glomeratum	5		8		16	14	17		19	8			18	15	8		3	20
Hormosina sp																		
Hyperammina elongata					2					3								
Labrospira crassimargo	41		8	43	24	71	13	21	12	15	25	17		5	13	20	14	11
L. jeffreysii				14	2					1	5	50			2	20	23	7
Lagena																		2
Nodosaria																		
Proteonina atlantica	36	50			5			5		18	21		18		8	20	9	18
Quinqueloculina frigida																		
Recurvoides turbinatus			8		8		7		21	8	18							
Reophax arctica															4			
R. curtus	18	50	71	29	40	14	57	7	45	19	24	34	65	78	63	40	51	31
R. scottii																		
Spiroplectammina biformis							3			1	4			2				4
Textularia torquata					3					1					1			
Trochammina advena									2		1							
T. quadriloba																		
Valvulina conica																		

STATION	43	48	52	53	54	55	58	61	62	65	67	68	71	73	76	80	82	85
DEPTH IN METERS	118	95	107	110	119	125	143	158	162	168	172	171	180	183	166	152	146	114
TOTAL LIVING BENTHONIC POPULATION	21	2	39	113	80	67	24	40	22	48	56	14	50	50	26	48	49	12
BENTHONIC SPECIES IN %																		
Ammodiscus ssp			5	.9	2	1		4					2			6	16	
Cassidulina norcrossi																		
Crithionina pisam var. hispida																		
Eggerella advena																		
Haplophragmoides bradyi			5	11	2	3		7				14	6	18	4	6		
H glomeratum		50	20	16	12	22	8	18	9	8			14	10	11	19		17
Hormosina sp	5																	
Hyperammina elongata						3									8		2	
Labrospira crassimargo	24		15	3	5	1	4	7	18	21	7	43	16	8		6	2	
L. jeffreysii	19			.9	2	3			9				2	18				
Lagena																		
Nodosaria	9																	
Proteonina atlantica	29		13	7	12	7	12				7		14	18	11	19	14	58
Quinqueloculina frigida																		
Recurvoides turbinatus				8	7	4			18	4	14		6	12				
Reophax arctica																		
R. curtus	14	50	33	43	47	34	75	55	45	54	64	43	34	16	61	37	61	25
R. scottii						1												
Spiroplectammina biformis			5		2	16		7		4			4					
Textularia torquata				7	5	1				4						6	4	
Trochammina advena			3															
T. quadriloba																		
Valvulina conica													2					

STATION	88	90	91	96	98	102	103	104	105	106	107	110	111	112	113	114	116	118
DEPTH IN METERS	100	93	66	88	96	117	110	109	108	107	105	99	98	96	94	93	87	90
TOTAL LIVING BENTHONIC POPULATION	44	40	9	5	24	16	49	14	3	15	74	13	42	15	28	14	18	10
BENTHONIC SPECIES IN %																		
Ammodiscus ssp					4													
Cassidulina norcrossi																		
Crithionina pisam var. hispida																		
Eggerella advena																		10
Haplophragmoides bradyi			11												7		11	
H glomeratum	24	2	22		33		4	7		20	13	8	10	20	29	29	44	
Hormosina sp																		
Hyperammina elongata																		
Labrospira crassimargo	10			60	12	12	6	21	33	7	5	23			7			10
L. jeffreysii		5									3							
Lagena																		
Nodosaria																		
Proteonina atlantica	7	40			8					20	3		29	33	21	36	11	
Quinqueloculina frigida												8		7				
Recurvoides turbinatus		5																
Reophax arctica								7			3							
R. curtus	48	47	33	20	25	56	88	36	33	20	49	38	38	27	29	29	11	50
R. scottii																		
Spiroplectammina biformis	7				8	12			33	13	3	15		13			11	
Textularia torquata	3		33	20	8	19		29		20	22	8	19		7		11	30
Trochammina advena																		
T. quadriloba							2											
Valvulina conica																		

Table 8. Distribution of species of living Foraminifera at stations 2–118

STATION	121	123	128	131	133	134	135	136	137	138	139	141	142	143	144	148
DEPTH IN METERS	89	90	76	73	73	76	75	73	73	70	69	67	65	64	61	74
TOTAL LIVING BENTHONIC POPULATION	8	1	5	3	3	5	1	4	1	5	4	6	9	5	29	1
BENTHONIC SPECIES IN %																
Ammobaculites cassis															17	
Ammodiscus ssp.																
Eggerella advena				67						20	25	33		20	17	
Haplophragmoides glomeratum	50		60	33		20				60						
Hippocrepina indivisa						20										
Labrospira crassimargo	12							75			50					
Proteonina atlantica											25			40	17	
Quinqueloculina frigida																
Recurvoides turbinatus																
Reophax arctica																
R. curtus	37	100	40		67	40	100	25	100			50	76	40	38	100
Spiroplectammina biformis					33	20				20		17	11		3	
Textularia torquata													11		7	

STATION	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168
DEPTH IN METERS	76	76	78	81	80	82	85	82	82	79	76	72	64	67	73	81	86	88	92	100
TOTAL LIVING BENTHONIC POPULATION	1	12	3	2	2	4	4	4	1	5	8	57	3	2	12	8	22	9	6	2
BENTHONIC SPECIES IN %																				
Ammobaculites cassis																				
Ammodiscus ssp.																				
Eggerella advena		8								40		2		50	17					
Haplophragmoides glomeratum					100		25	25		40	25	12			8	12		33		
Hippocrepina indivisa																				
Labrospira crassimargo		8						25			25	10			8		27	22		50
Proteonina atlantica												12		50						
Quinqueloculina frigida																				
Recurvoides turbinatus																			17	
Reophax arctica		8				25									17				17	
R. curtus		17	100	50		75	50	50		20	37	51			8	12	73	22	50	
Spiroplectammina biformis		33		50							12	7	67		8	37		22	17	50
Textularia torquata	100	25					25		100			5	33		33	37				

STATION	169	170	173	175	176	178	181	182	183	184	185	186	190	192	194	196	201	203
DEPTH IN METERS	98	96	87	80	64	73	90	98	92	92	92	99	92	86	76	67	64	89
TOTAL LIVING BENTHONIC POPULATION	13	11	11	28	1	25	9	14	28	29	3	15	6	3	2	28	70	16
BENTHONIC SPECIES IN %																		
Ammobaculites cassis																		
Ammodiscus ssp.										3								18
Eggerella advena				4												11		
Haplophragmoides glomeratum	15		9			12	22	64	11	28		7				45	29	18
Hippocrepina indivisa																		
Labrospira crassimargo	62	9		4		4			4	7		27	33				14	9
Proteonina atlantica			9			4	11										6	
Quinqueloculina frigida																3		
Recurvoides turbinatus							22							33			3	9
Reophax arctica		9														3		
R. curtus	15	27	18	21	100	80	33	21	29	48	100	40	50		50	11	26	18
Spiroplectammina biformis	8	36	18	18					25	3		13	17		50	28	20	9
Textularia torquata		18	45	54			11	15	32	10		13		67		6	3	18

Table 9. Distribution of species of living Foraminifera at stations 121–203

STATION	205	207	213	215	219	221	222	228	230	231	234	236	239	250	253	254	255	256	259	261	263	265	284	287	474	478
DEPTH IN METERS	84	150	109	100	85	78	70	87	99	100	122	122	131	132	143	145	148	152	174	174	174	174	171	162	58	87
TOTAL LIVING BENTHONIC POPULATION	24	2	104	35	111	40	79	23	84	36	52	26	54	36	1	11	26	27	69	86	30	24	80	6	8	28
BENTHONIC SPECIES IN %																										
Ammobaculites cassis	4																									
Ammodiscus ssp.	4				3					3						9	8		4	5	3		2			
Crithionina pisam var. hispida									2																	
Eggerella advena							2																			
Haplophragmoides bradyi																9	8			2	3	25	10			
H. glomeratum	25	50	11	11	19	10	36	22	25	36	58	11	7	42	100	18	23	11	35	21			32	67	37	29
Hyperammina elongata																						12				
Labrospira crassimargo	8		23	9	11	10	2	9	9	8		19	18	11		9		33	17	5		25	7		12	7
L. jeffreysii				3	11		4	4		11		15		8						2			2			29
Proteonina atlantica	4				5	12	24	35	16	25	4	8	7	14		18	8		4		20		2		12	7
Quinqueloculina frigida					5		2																			
Recurvoides turbinatus				3	5	2					8		11	3		18	23			16	3	12	30			7
Reophax arctica			2	3					2																	
R. curtus	42	50	52	66	32	50	17	13	32	17	27	46	44	14		9	23	56	30	32	60	12	10		25	21
Spiroplectammina biformis	4		10		5		7	4	5		4		11	8		9			4	7	10	12				
Textularia torquata	4		2	6	3	12	6	13	9								8		4	9			2	33	12	
Trochammina squamata						2																				

STATION	480	482	494	496	506	507	508	512	520	521	522	523	525	526	528	529	530	531	533	534	535	540	541	543	544	562	564	566
DEPTH IN METERS	73	97	144	152	148	137	128	100	59	69	79	84	85	97	96	105	110	113	128	134	140	170	170	169	170	93	93	100
TOTAL LIVING BENTHONIC POPULATION	2	6	3	18	45	49	68	84	67	10	5	13	20	12	24	44	70	45	58	22	33	9	42	24	11	36	28	24
BENTHONIC SPECIES IN %																												
Ammobaculites cassis																												
Ammodiscus ssp.						2	1								4	2		17	3		6			8				
Crithionina pisam var. hispida																												
Eggerella advena									24	10				8		2												
Haplophragmoides bradyi				6			19										4	6	3						18			
H. glomeratum		67	67	17	33	20	18	57	3	20	40		45	8	62	41	20	6	17	18	24	22	29		18	3	16	17
Hyperammina elongata				11												2					3							
Labrospira crassimargo	100			6	27	2	3	4	6				10		8	9	9	17	9	36	18	22	7		9	17	16	8
L. jeffreysii			33					7									17	6	2		3				9		5	
Proteonina atlantica				22	13	14	31	14	9						17	14	16		29		3				18		10	33
Quinqueloculina frigida																												8
Recurvoides turbinatus						8		4					5						5		3	22	29					
Reophax arctica																								8				8
R. curtus				33	27	49	21	14	45	60	40	46	35	33	4	25	29	33	19	36	36	22	7	75	27	67	37	25
Spiroplectammina biformis						2	4		7			23		8	4	2	4	6	7	9	3	11	21			3	5	
Textularia torquata		33		6		2	3		6	10	20	31	5	42		2		6	5				7	8		11	10	
Trochammina squamata																												

Table 10. Distribution of species of living Foraminifera at stations 205–566

STATION	569	572	573	575	577	580	585	587	595	598	600	601	602	618	621	623	625	626
DEPTH IN METERS	116	143	137	158	158	171	158	142	160	168	167	78	46	77	90	82	111	120
TOTAL LIVING BENTHONIC POPULATION	60	21	26	78	20	22	42	25	52	34	99	31	25	75	108	42	26	19
BENTHONIC SPECIES IN %																		
Ammodiscus ssp.		5	8										4					
Crithionina pisum var hispida									8									
Eggerella advena												6		4				
Haplophragmoides bradyi				11	10	9	21		8		21						4	10
H. glomeratum	15	38	23	11	10	36	36	28	4	6	21	39	20	28	25	43	8	
Hormosina sp.											9							
Hyperammina elongata				4														
Labrospira crassimargo	8		8	15			14	12	4		15		4	4		7	38	15
L. jeffreysii	20			4				8	11	18					14		4	
L. cf. nitida																		
Proteonina atlantica	17	24	15	8				8	8	12	6		8	8	14	21	19	31
Quinqueloculina frigida																		
Recurvoides turbinatus	3		8	8	10		21	28	15	12	6	3			3	7	4	5
Reophax arctica															3			
R. curtus	23	19	23	35	50	45	7	8	31	53	21	42	48	32	39		8	36
Spiroplectammina biformis		9	15	4	20	9						3	16		3	7	11	
Textularia torquata	13	5							11			6		24		7		
Trochammina advena																	4	
T. quadriloba																		
Valvulina conica								8										

STATION	629	632	634	648	649	653	654	656	658	660	662	663	664	665	666	667
DEPTH IN METERS	140	152	152	142	150	168	181	152	145	126	125	118	111	102	92	75
TOTAL LIVING BENTHONIC POPULATION	72	22	96	10	12	18	8	7	17	43	10	34	31	4	6	33
BENTHONIC SPECIES IN %																
Ammodiscus ssp.																
Crithionina pisum var hispida																
Eggerella advena																
Haplophragmoides bradyi	12		2			6		29								
H. glomeratum	17	36	4	10	8	39	12	14		24		18	16	25	16	45
Hormosina sp.									6							
Hyperammina elongata									6							
Labrospira crassimargo	8		29	10	50	22	12		18	18	10	29	10			9
L. jeffreysii	4	9											6			
L. cf. nitida			2													
Proteonina atlantica	17		4	10	17	6			53	12	50	12	10	25	50	3
Quinqueloculina frigida																3
Recurvoides turbinatus		18	35	10		6	25	14		6		6				
Reophax arctica										6						
R. curtus	38		19	50	25	6	25	43	18	18	30	12	39	50	33	33
Spiroplectammina biformis	4	18	4	10		11	25				10	12	10			
Textularia torquata		18				6				6		12	6			6
Trochammina advena										6			3			
T. quadriloba																
Valvulina conica																

STATION	688	691	697	703	722	723	724	725	726	727	728	729	730	731	732	733	734
DEPTH IN METERS	150	152	146	107	134	136	150	150	150	142	133	138	144	122	113	131	110
TOTAL LIVING BENTHONIC POPULATION	38	51	11	33	22	19	39	22	78	10	10	40	28	14	8	16	3
BENTHONIC SPECIES IN %																	
Ammodiscus ssp.	5		9						8				7	7		6	
Crithionina pisum var hispida																	
Eggerella advena																	
Haplophragmoides bradyi	5		27									10	14				
H. glomeratum	16	18	9	33	9	16	15	18	8	20		20	7	36	25	56	
Hormosina sp.																	
Hyperammina elongata							3										
Labrospira crassimargo	47	24	9	6	14	5	5	27		20		5	7	21	38		
L. jeffreysii									3			10	7				33
L. cf. nitida																	
Proteonina atlantica	5	12	27	14			3		10	20	60	25	7	7	12	12	33
Quinqueloculina frigida																	
Recurvoides turbinatus					5		3		13			10			12	6	
Reophax arctica																	
R. curtus	5	35		20	32	63	46	27	26	20	20	10	36	7			
Spiroplectammina biformis	16	6	18	9	27	5	18	18	5	10	20	5		14			
Textularia torquata		6		9	14	5	8	9	28			5	7	7		6	
Trochammina advena																	
T. quadriloba						5										12	
Valvulina conica															12		33

Table 11. Distribution of species of living Foraminifera at stations 569–734

Table 12

Foraminifera species found living, listed in decreasing order of abundance.

Species	*No. of Stations*
Reophax curtus	182
Haplophragmoides glomeratum	160
Labrospira crassimargo	142
Spiroplectammina biformis	111
Proteonina atlantica	106
Textularia torquata	98
Recurvoides turbinatus	67
Labrospira jeffreysii	49
Haplophragmoides bradyi	44
Ammodiscus	42
Crithionina pisum var. *hispida*	16
Reophax arctica	14
Hyperammina elongata	12
Eggerella advena	10
Quinqueloculina frigida	7
Trochammina advena	6
Valvulina conica	4
Trochammina quadriloba	4
Hormosina sp.	3
Ammobaculites cassis	2
Trochammina squamata	1
Labrospira cf. *nitida*	1
Lagena	1
Nodosaria	1
Cassidulina norcrossi	1
Hippocrepina indivisa	1

STATION	2												9										26									
DEPTH IN METERS	110												143										110									
SAMPLE	2	3	4	5	6	7	8	9	10	11	12	13	1	2	3	4	5	6	7	9	11	12	1	2	3	4	5	6	8	9	10	11
POSITION IN CORE IN CM. FROM TOP	4-8	8-12	12-16	16-20	20-23.5	23.5-27	27-31	31-35	35-39	39-43	43-47	47-52	0-2	2-4.5	4.5-7.5	7.5-9.5	9.5-14	14-17.5	17.5-20	23.6-26	28-31.5	31.5-35	0-4	4-6.5	6.5-8.5	8.5-12.5	12.5-15	15-18	21-24	24-27	27-30	30-32
TOTAL PLANKTONIC POPULATION			10			15			12	9	16	9					1															2
PLANKTONIC SPECIES IN %																																
Globigerina bulloides			80			100			33	100	75	33																				100
G. pachyderma			20						67		25	67																				
G. sp.																	100															
TOTAL BENTHONIC POPULATION	771	662	508	677	955	579	872	363	792	1307	1600	1164	187	104	68	63	174	166	55	64	125	77	125	215	324	448	278	334	208	264	128	262
BENTHONIC SPECIES IN %																																
Ammodiscus ssp.													2		1								.8	.5		.7						
Angulogerina angulosa																										4						
Astrononion stellatum		3	2	.9		.5	.5	.2											2									.6				
Bolivina pseudopunctata									.5	.5		.3																				
B. subaenariensis								.8			.3						3	7			2				.6	3					2	.8
Bulimina aculeata																	7	14	7						15	13	.7	.6				
B. marginata		.6	4			.5	.5			.7	1	7																				
Cassidulina algida		1	1	.5		1											1	1	2	2	6				2	3	3	4	5	6	3	5
C. islandica var. minuta		.6	2	8	4	7	7	3	6	6	8	24						.6										.6				
C. norcrossi		9	9	13	9	12	16	12	14	34	22	28					3	6	5						.6	1	1	5	1	3	2	.8
Cibicides lobatulus									.5									.6	2						.6	.7	1	1		.7	.8	4
Cornuspira	.4	.3																														
Eggerella advena													.5										2	.9								
Elphidium articulatum																		.6														
E. incertum var. clavatum			5	3	1	8	8	2	4	2	.8	1						.6										1		2	.8	2
E. subarcticum																										1	2					
Eponides frigidus		1	5	6	2	3	2	.8	1	.2	.8	.8														.7		.6	2			
E. umbonatus												.8																				
Globobulimina auriculata		12	18	16	31	19	18	21	9	8	5	5					9	28	27	2	26				3	19	30	27	10	24	19	30
Haplophragmoides bradyi			4										4	9	1	5	.6						.8	6	19	4		.6				
H. glomeratum	38	17	2	2	.5								20	15	62	38	20	5	13	42	6	38	30	29	17	3	2		1			
Hyperammina elongata																							.8									
Labrospira crassimargo	14	13	.4										26	37	13	27	14	2	11	8	5	19	17	30	13	8	1	2				
L. jeffreysii	1	.9				2							2	6			1			5			2	2	7	4						
Lagena		9	.4					.8	.5	.9	1	1						.6								1	.7	.6			.8	
Nonion labradoricum		11	39	28	26	26	34	31	27	20	26	11					16	25	18		29				2	22	31	26	25	38	21	29
Nonionella auriculo						.5		.8	.5																			.6				
Proteonina atlantica	39	37	14	16	23	8	16	12	10	9	5	2	19	18	6	25	21	7	9	33	20	38	42	24	12	15	25	26	54	23	44	25
Pullenia bulloides						3	.9	.8	2	2	3	.5																				
Recurvoides turbinatus													18	10	12	2	2			6	5	3	2			.7						
Reophax curtus	4	1	.8	1		5	.5						10	5	4	4	.6	.6	4	2	2	3	5	4	1	.4		.6	1	.7	5	.8
Spiroplectammina biformis	3	.6	4										.5							2				.9	.6	.4						
Textularia torquata	.4																															
Trochammina advena																							.8	1	4	.7						
T. lobata													.5																			
T. squamata																							.8						.5			
Virgulina complanata				1	.5	.3	4	7	20	15	22	13					.6															
V. fusiformis		.3	.4	3	1	6	2	7	3	.9	2	4																				

Table 13. Distribution of Foraminifera in cores 2, 9, and 26

STATION	27											47														68								
DEPTH IN METERS	104											96														171								
SAMPLE	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	12	13	14	2	3	5	6	8	10	11	12	13
POSITION IN CORE IN CM. FROM TOP	0-3	3-7	7-11	11-12	12-13	13-16.5	16.5-19	19-21	21-24.5	24.5-29.5	29.5-32	0-3.5	3.5-7.5	7.5-11.5	11.5-12.5	12.5-14	14-15.5	15.5-17	17-20.5	20.5-24	24-28	28-32.5	32.5-36.5	36.5-41	41-44.5	7.5-10.5	10.5-14	13-14.5	20-23	26-27.5	31.5-34.5	34.5-37.5	37.5-40	40-42.5
TOTAL PLANKTONIC POPULATION			3	2	8	15	16	56	9		24							8											5					
PLANKTONIC SPECIES IN %																																		
Globigerina bulloides						60	75	57	100		100							100																
G. eggeri						20	12	29																										
G. inflata						20	12	14																										
G. sp.			100	100	100																								100					
TOTAL BENTHONIC POPULATION	98	116	213	82	270	760	348	2354	438	1012	812	172	376	265	198	244	296	240	488	201	438	960	408	672	394	78	63	165	245	47	99	105	139	42
BENTHONIC SPECIES IN %																																		
Ammobaculites cassis												.6																						
Angulogerina angulosa								.3																								1		
Astrononion stellatum					1		.5		.7							2			.8									2	.4	2				
Bolivina subaenariensis																										1				2				
Bulimina aculeata			1				2						.8	1							7	.3		1		1			.4	4				
Cassidulina algida			1			3		.3	5	2		6	2	1	4	7	3		4	15	7	2	3	1	1	1			8		1		4	
C. islandica var. minuta			4	7	21	14	8	8	11	16	12													6	2			15	8	4	4	9	14	
C. norcrossi			17	40	39	41	36	33	38	32	8		.8				1			4	8	32	1	8	17			31	41	17	18	28	6	5
Cibicides lobatulus			3		1		3	3	2	1	1										7							2	.8					
Eggerella advena	4	3			7		.5					6																				1		
Elphidium articulatum																2																	7	7
E. incertum var. clavatum				2	3	4	2	4	2	5	10		.8	4		2			2		1	3	2	6				39	12	2	60	50	42	69
E. subarcticum						.8	5	3	7						1						.7										4		7	
Eponides frigidus			1	7	6	11	9	8	3	7	19		2	4	6	5	1	3	4	4	4	7	7	4	9									
Globobulimina auriculata			22	12	6	10	9	7	14	8	5	28	55	39	55	59	46	39	61	34	45	33	48	39	39	13	6		5	13				
Haplophragmoides bradyi	2																																	
H. glomeratum	28	21	3									24	3	8	3		3		.8	1						3	8							
Labrospira crassimargo	5	21	6									10	8	6	4	2	4	18								4	29							
L. jeffreysii												6		1		2																		
Lagena			3	2		1	3	.7	1		2	6		1	1		4			1	2	2	1					.6			1			
Miliolids																				6													.7	
Nonion labradoricum			17	14	8	5	14	28	13	22	32	3	25	25	10	16	30	21	21	22	20	13	20	23	14	6	6	4	24	28	8	10	30	19
Nonionella auricula						1	2	5		8	2																		.4					
Proteonina atlantica	36	46	15	12	3	1	2	2	3	3	5	12	6	3	6	5	3	10	3	3	6	5	9	11	11	69	43		2	26				
Quinqueloculina seminula										4																								
Recurvoides turbinatus	1		1																							1								
Reophax curtus	2	2										11	2	1				3		3	.7	.3					4			2				
Robulus																							2			1	5	4						
Spiroplectammina biformis	2	3	1									5	.8																					
Textularia torquata	16	3										1																						
Triloculina tricarinata						.8	1																											
Trochammina squamata	2		3		2	.8		1			.5	2																	.4					
Virgulina complanata					3	3	3	2	4	2	4	.6	2	2	3		4	3	2					.6				2	2		4		.7	
V. fusiformis														2	3				.8	4	1	2	1	6	6									

Table 14. Distribution of Foraminifera in cores 27, 47, and 68

STATION	77											91														130					
DEPTH IN METERS	164											66														69					
SAMPLE	1	2	3	4	6	7	9	10	11	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6
POSITION IN CORE IN CM FROM TOP	0-3	3-7	7-10	10.5-13.5	15-17	17-22	27-33	33-36	36-38	43-48	48-54.5	0-4	4-7	7-10	10-13.5	13.5-15.5	15.5-19	19-22.5	22.5-26.5	26.5-29.5	29.5-32.5	32.5-35	35-36.5	36.5-38.5	38.5-41.5	1-3.5	3.5-6	6-9	9.5-14	14-18	18-21.5
TOTAL PLANKTONIC POPULATION				6		1		1	2							2	3														
PLANKTONIC SPECIES IN %																															
Globigerina bulloides				67				100																							
G. pachyderma									100																						
G. sp.						100										100	100														
Globorotalia scitula				33																											
TOTAL BENTHONIC POPULATION	148	222	366	198	11	65	28	36	47	15	22	86	86	203	181	152	390	270	246	180	387	93	49	82	117	124	98	165	248	138	96
BENTHONIC SPECIES IN %																															
Ammodiscus ssp.	.7	2	2																							2					
Angulogerina angulosa											9					1	2			2		3									
Astrononion stellatum				1	18	1	14										1				.8										
Bolivina subaenariensis			.3	2																											
Bulimina aculeata				6	18	3			2																						
Cassidulina algida				10		8			13									1	1	5	4	1		5	2				.8		1
C. islandica var. minuta				1		29	43	83	38	53	36					4	7	1										.6			
C. norcrossi			.5	3		9										1			2	2	2			5							1
Cibicides lobatulus														.5		5	1	1	4	3	1			2							
Eggerella advena												28	29	30	49	5	4	2	2		1	21	39	10		44	43	27	39	41	41
Elphidium articulatum														.5						1											
E. incertum var. clavatum						11		5	2		4		1	1		3	3	3	2	5	6	4		2	2					.7	2
E. subarcticum																	.8	1	1	3	1	2		2	9			1	.8		
Eponides frigidus				1										1	3	20	8	11	18	10	7	10		5	12			1	5	2	4
Globobulimina auriculata				25		4			17		9		9	8	17	36	44	39	40	33	47	32	20	46	44			10	2	9	3
Haplophragmoides bradyi	28	.9	1																												
H. glomeratum	52	17	34	4					2	7		3	3	11	1		2									2	3	1		2	
Labrospira crassimargo	15	52	45	2					2			2	1	.5	1								4			8	1	1		2	
L. jeffreysii		.9	1											1		1	.8														
Lagena				2		3			2				1		1	1	8	2	1	2	1				5						
Miliolids						1																						1			
Nonion labradoricum				26	55	26	39	11	19	40	41		5	2	4	15	12	21	11	10	18	10	8	7	5			7	10	4	12
Proteonina atlantica	.7	22	9	9								1		1	2	3	3	8	7	8	2	6	12	7	10	2	2	.6			3
Recurvoides turbinatus												1		1																	
Reophax curtus	2	3	1	1								5		.5												.8	2	1	2		
R. scottii												5	2	3	3											23	16	6	5	4	
Robulus																					.8										
Spirillina arctica												2																			
Spiroplectammina biformis			3	1								16	20	16	4								8			11	11	9		6	2
S. typica																												2			
Textularia torquata	.7		.5									31	28	14	10	4	1					6			9	11	11	8	12	13	6
Triloculina tricarinata							4																								
Trochammina lobata																										.8		1			
T. squamata												5		7	4		2	3	2		2	3	8	2	10	3	10	22	18	11	13
Valvulina conica		1	2	1																											
Virgulina complanata				6	9	3			2					.5																	
V. fusiformis														.5		1	5	6	7	16	3			5	7			1	8	4	10

Table 15. Distribution of Foraminifera in cores 77, 91, and 130

STATION	140									171											190												
DEPTH IN METERS	68									93											92												
SAMPLE	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	12	13
POSITION IN CORE IN CM. FROM TOP	0-3	3-5.5	5.5-8	8-10.5	10.5-13	13-16	16-18.5	18.5-21	21-24	0-4.5	4.5-7	7-9	9-11.5	11.5-14.5	14.5-18	18-21.5	21.5-24	24-27.5	27.5-31	31-34.5	0-2.5	2.5-5.5	5.5-9	9-11	11-14	14-17	17-19	19-21.5	21.5-25	25-28	28-30.5	30.5-32.5	32.5-35
TOTAL PLANKTONIC POPULATION															2	13	8															1	
PLANKTONIC SPECIES IN %																																	
Globigerina eggeri																100																100	
G. sp.															100		100																
TOTAL BENTHONIC POPULATION	150	117	98	153	163	51	63	59	55	51	55	52	74	128	308	389	322	354	310	180	22	28	31	26	110	63	11	182	9	288	159	116	240
BENTHONIC SPECIES IN %																																	
Ammobaculites cassis					2																		3										
Ammodiscus ssp.			3																														
Angulogerina angulosa																.2	.6	.6															
Astrononion stellatum												10																					
Cassidulina algida									2						.9	5	.6	1	.6	2					.9			2		1	2	2	5
C. islandica var. minuta														.8																			
C. norcrossi																												4		4	4	8	4
Cibicides lobatulus								2							.6			.6															
Eggerella advena	33	16	34	30	45	53	36	46	11		2					.2			.6			4	3			5				.3			
Elphidium articulatum															.9																		
E. incertum var. clavatum						2		5	4						.9	7	5	3	3	11								.6		3	1	5	8
Eponides frigidus					1	6	2	2	7					4	8	15	11	10	7	10					9			2		6	3	5	8
Globobulimina auriculata				1			19	2	15			2	13	23	32	34	33	17	32	26					42			36		21	33	29	35
Haplophragmoides glomeratum	3	3	4	5	2		2	2	4	57	36	40	28	16	8	7	11	18	15	7	50	36	48	50	20	32	18	3	44	9	2	3	2
Labrospira crassimargo	5		3		2					16	15		5	7	6	1	4	3	4	7	9	18	16	23	11	44	9	3	11	.7	.6	2	2
L. cf. jeffreysii											4	4	3		.6			.6															
Lagena															.6	.5		.6		.6										.3			
Miliolids																.2																	
Nonion labradoricum				3	.6		5	3	11			4	22	41	36	25	30	36	30	32					17			45		46	48	41	32
Polymorphinidae																			1														
Proteonina atlantica	4	10	3	.7	5	4	5	5	9	8	9	2	9	2	1	1	.[illegible]	4	3	2	14	18	10	4	3	8	36	2	22	5	.6		.8
Recurvoides turbinatus										8	16	17	9	3	2	.7	3	4	1	3	5	11	10			8	9	1	11	1	.6	3	
Reophax curtus		.9	2						4	8	16	6	8	4	.3	.5		2	1	.6	5	4	6		2	2	27	1	11	1	1	.9	
R. scottii	14	24	15	8			5	7																									
Robertina cf. charlottensis															.3																		
Spiroplectammina biformis	15	20	17	21	13	4		8		4	2	12			.3						14	4	3		.9	2							
S. typica				1		2	2												.6					4									
Textularia torquata	19	14	14	22	18	6	5	7	2																								
Trochammina lobata		3		1																													
T. squamata	7	7	4	5	9	20	21	7	18			2	1								5	7			.9						1		
Virgulina complanata																	.6											.6		1	.6		
V. fusiformis				1	1	4		5	15						.6	1									.9			.6				.9	2

Table 16. Distribution of Foraminifera in cores 140, 171, and 190

STATION	474						495							573						
DEPTH IN METERS	58						145							137						
SAMPLE	1	2	3	4	5	6	1	2	3	4	5	6	7	1	2	3	4	5	6	7
POSITION IN CORE IN CM. FROM TOP	0-3	3-7	7-10	10-13	13-15·5	15·5-18	0-2	2-5	5-8	8-12	12-13·5	13·5-15·5	15·5-19	0-2·5	2·5-5	5-7·5	7·5-10	10-13	13-17	17-20
TOTAL PLANKTONIC POPULATION			1								9	8	1							4
PLANKTONIC SPECIES IN %																				
Globigerina bulloides			100																	
G. eggeri											100									
G. sp.												100	100							100
TOTAL BENTHONIC POPULATION	175	137	166	163	8	3	78	58	73	115	115	147	281	27	59	91	62	133	340	439
BENTHONIC SPECIES IN %																				
Ammobaculites cassis	1	.7	2	1																
Ammodiscus ssp.				.6			1	3												
Angulogerina angulosa										.9			.4					.8	.3	
Astrononion stellatum													.4							
Bolivina subaenariensis												.7	2							
Bulimina aculeata										5	.9		1					2	.9	2
Cassidulina algida										.9	5	3	15					6	9	7
C. norcrossi										.9	2	3	9					1	3	3
Cibicides lobatulus													4							
Eggerella advena	49	66	66	55	12	33														
Elphidium articulatum																			.6	
E. incertum var. clavatum										3	5	3	7						1	.9
Eponides frigidus				1						6	.11	8	8					10	8	7
Globobulimina auriculata				2						25	26	21	20					26	23	27
Glomospira gordialis	1																			
Haplophragmoides bradyi							3							4						
H. glomeratum	11	8	8	3		33	35	29	36					22	49	64	11			
Labrospira crassimargo	6	1	2	.6			10	10	3						29	2	34			
L. jeffreysii	.6		.6				3													
Lagena											.9	.7	.4					.8		.2
Miliolids												1								.2
Nonion labradoricum										19	34	43	28					44	47	40
N. sp.																				2
Polymorphinidae													.4							
Proteonina atlantica	10	13	9	26	75	33	35	45	47	28	13	12	6	67	20	25	44	9	7	9
Recurvoides turbinatus	3		.6				14	10	12							3	10			
Reophax arctica	1																			
R. curtus	3	1	1	1				2		3				4	2	1	2			
Robertina cf. charlottensis												2	.7							
Spiroplectammina biformis	11	4	8	4	12											3				
S. typica				3																
Textularia torquata	2	1												4		1				
Trochammina squamata	.6	4	2	1																
Virgulina complanata										.9	.9	1	2						.3	.2
V. fusiformis				2								.7								

Table 17. Distribution of Foraminifera in cores 474, 495, and 573

STATION	595						648							732										
DEPTH IN METERS	160						142							113										
SAMPLE	1	2	3	4	5	6	1	2	3	4	5	6	7	1	2	3	4	5	6	7	8	9	10	11
POSITION IN CORE IN CM. FROM TOP	0-3	3-6·5	6·5-8·5	8·5-11·5	11·5-13·5	13·5-15·5	0-3	3-6	6-9	9-12	12-15	15-18	18-21	0-2·5	2·5-4·5	4·5-7·5	7·5-9·5	9·5-12	12-16	16-18	18-20	20-22	22·5-25	25-27
TOTAL PLANKTONIC POPULATION					7	3																3		
PLANKTONIC SPECIES IN %																								
Globigerina bulloides					29																			
G. eggeri					71	33																		
G. inflata																						33		
G. sp.						67																67		
TOTAL BENTHONIC POPULATION	70	54	110	82	170	105	212	143	53	8	99	433	354	112	40	66	77	266	112	5	5	160	11	2
BENTHONIC SPECIES IN %																								
Ammodiscus ssp.		2					·9	2							2									
Angulogerina angulosa												.5						.8	2			.6		50
Bolivina subaenariensis			2	1														.8						
B. sp.						.9																		
Bulimina aculeata			4	5	16	5						.5	.6											
B. marginata																		9	8			.6		
Cassidulina algida			3	15	8	14					4	8	14				1	.8	2			2		
C. islandica var. minuta																	1	7	.9		20	4		
C. norcrossi			3		1	3					1	3	4				1	38	29			19	18	
Cibicides lobatulus				1	2	.9					3	2	5											
Eggerella advena	1	4	2				6	6	4	12				2										
Elphidium articulatum				1	6	4					1	.2							10		20	3	45	
E. incertum var. clavatum					.6	2						.2	1				1	4	.9	20	60	2	9	50
E. sp.													.3						.9	20				
Eponides frigidus			.9	7	5	11					5	2	5				3	9	8			5	9	
Globobulimina auriculata			6	18	28	28					59	42	26				18	4	7	20		16		
Glomospira gordialis								.7																
Haplophragmoides bradyi	7	2					.5																	
H. glomeratum	37	15	43	2			55	39	7			.2		63	27	21	1		3			.6	9	
Labrospira crassimargo	9	6	5		.6		4	.7	13			.2		.8		14			.9	20			9	
L. jeffreysii							.5	.7									1							
Lagena					1						2											.6		
Miliolids					1	.9																		
Nonion labradoricum			7	22	24	21					12	36	42				1	14	12			37		
Proteonina atlantica	33	59	18	21	3	7	9	11	47	62	5	2	.3	25	57	56	64	8	10	20		5		
Recurvoides turbinatus	10	13	2				2							2										
Reophax curtus	1		.9				.9							2	4	2	3							
R. scottii							.9	.7																
Spiroplectammina biformis							3	10						3	5				.9					
S. typica							.5				1	.2				1			.9					
Textularia torquata							6	6																
Triloculina tricarinata						.9																		
Trochammina lobata							3	.7																
T. squamata	1		2	4	2	2	7	22	28	25	7	3	.8	3	2	6	4	.8				.6		
Virgulina complanata			.9	2		.9						.2	.6					4	4			1		
V. fusiformis																						.6		

Table 18. Distribution of Foraminifera in cores 595, 648, and 732

No. 9 — *Foraminifera Species Off Portsmouth, New Hampshire*[1]

By Frances L. Parker

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INTRODUCTION

The species discussed in this paper are, for the most part, those used by Phleger in his study of the ecology of Foraminifera off Portsmouth, N. H. Some species groups that he has combined have been divided for discussion because of interesting occurrences. A few rare species are included for the same reason. The types are deposited at the U.S. National Museum in Washington, D. C.

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[1] Manuscript received for publication October 2, 1951.

N6onr-277, Task Order III. Miss Jean Peirson assisted in preparation of the material.

Locations of the samples are in Phleger's paper (see above). The area between latitudes 43°7'N and 42°41'N and longitudes 70°04'W and 70°47'W has been very extensively sampled with the exception of the southeastern portion in the vicinity of Jeffreys Ledge. This area is shown on the U. S. Coast and Geodetic chart, Portsmouth to Cape Ann, published in May, 1941 (5th edition).

PLANKTONIC FAUNA

The planktonic fauna of the Gulf of Maine is almost negligible and the species are not discussed. The specimens are mostly immature forms occurring in about 5 per cent of the samples. The species represented are: *Globigerina bulloides* d'Orbigny, *G. eggeri* Rhumbler, *G. pachyderma* (Ehrenberg), and *Globigerinoides rubra* (d'Orbigny).

BENTHONIC FAUNA

General Statement

The benthonic fauna is closely related to Arctic faunas to the north and to the faunas south of the Cape Cod barrier. Approximately 25 per cent of the species discussed are found in the Arctic, 35 per cent occur only south of Cape Cod and 30 per cent occur in both regions. The fauna is not a large one since the area is relatively small and the greatest depths are less than 200 m. For this reason it is difficult to give an adequate comparison with the southern fauna. It is well known, however, that Cape Cod forms a barrier for many of the warmer water species occurring to the south.

No samples were taken in the small bays of the area and species characteristic of such environments only are not present. An example of this is *Eponides frigidus* (Cushman) var. *calidus* Cushman and Cole which is abundant in some shallow bays of the area. A few species, however, usually associated with marsh or river faunas are found near the mouths of the rivers, such as *Trochammina macrescens* H. B. Brady and *Miliammina fusca* (H. B. Brady).

In addition to the 71 species from the Portsmouth area discussed below, two new species, *Labrospira arctica* and *Trochamminella atlantica*, have been described from the Arctic. Cushman's classification has been followed in the arrangement of the genera.

Discussion of species

Family ASTRORHIZIDAE

CRITHIONINA PISUM Goës var. HISPIDA Flint

(Plate 1, figure 1)

Crithionina pisum Goës var. *hispida* Flint, 1897 (1899), Ann. Rept., U. S. Nat. Mus., p. 267, pl. 6, fig. 2.

The Portsmouth specimens have fewer sponge spicules in the wall of the test than those figured by Flint. This is true also of specimens found by Höglund (1947, p. 36) in Swedish waters. The species is found at scattered stations in the North Atlantic. It is very rare in the Portsmouth area.

Family SACCAMMINIDAE

PROTEONINA ATLANTICA Cushman

(Plate 1, figure 2)

Proteonina atlantica Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 5, pl. 1, fig. 4.

Reophax difflugiformis H. B. Brady (part), 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 289, pl. 30, fig. 5 (not figs. 1–4).

Proteonina difflugiformis (part) of authors.

This species is much more coarsely arenaceous, is less flask-like in shape, and has a less pronounced neck than *P. difflugiformis* (H. B. Brady). A study of paratypes at the Cushman Laboratory showed that many of the specimens have a more prolonged neck than does the holotype. The wall of the Portsmouth specimens is very rough and is formed of angular quartz grains, sometimes up to 0.5 mm. in length, cemented with fine siliceous cement. The species is a common one south of Cape Cod and also occurs in the Arctic.

PROTEONINA DIFFLUGIFORMIS (H. B. Brady)

(Plate 1, figure 3)

Reophax difflugiformis H. B. Brady, 1879, Quart. Jour. Micr. Sci., vol. 19, p. 51, pl. 4, figs. 3a-b.; 1884 (part), Rept. Voy. CHALLENGER, Zool., vol. 9, p. 289, pl. 30, figs. 1–4 (not fig. 5).

This species differs from *P. atlantica* in its flask-like shape with a definite neck and in having a fairly fine-grained, smoothly finished wall. Occasional large grains are included in the surface of the wall but they are usually cemented flush with the surface. It is not common in the Portsmouth area. It is difficult to give the distribution of the species owing to its having been so often combined with *P. atlantica*. Apparently the latter is the more common species in northern waters of the Atlantic.

URNULINA COMPRESSA Cushman

(Plate 1, figure 4)

Urnulina compressa Cushman, 1930, Bull. 4, Florida State Geol. Surv., p. 15, pl. 1, figs. 2a, b.

Millettella spinata Cushman and McCulloch (not Cushman and Cahill), 1939, Allan Hancock Pacific Exped., vol. 6, no. 1, p. 43, pl. 2, figs. 1, 2.

Only a single specimen of this species was found. The only previously reported occurrence is from the Miocene of Florida. This specimen is identical with the holotype, with which it was compared at the Cushman Laboratory. The form figured by Cushman and McCulloch as *Millettella spinata* from the Pacific is apparently identical. The aperture of these forms appears to be more terminal than is that of the holotype as figured by Cushman and Cahill. The species is also found in rivers flowing into Long Island Sound. Since the Portsmouth specimen occurs at a station at the mouth of the Merrimack River it is probable that the form is limited to a brackish water environment.

Family HYPERAMMINIDAE

HIPPOCREPINA INDIVISA Parker

(Plate 1, figure 5)

Hippocrepina indivisa Parker, 1870, in Dawson, Canadian Nat., n. ser., vol. 5, p. 176, fig. 2.

This species is very rare. It is interesting to note that Cushman (1944, p. 6) found it to be very abundant at one station in the Gulf of Maine, off Eastport. It is recorded to the north ranging to the Arctic and from Albatross station D2018, off the coast of Maryland at 1440 m. (Cushman, 1918, p. 58).

HYPERAMMINA ELONGATA H. B. Brady

(Plate 1, figure 10)

Hyperammina elongata H. B. Brady, 1878, Ann. Mag. Nat. Hist., ser. 5, vol. 1, p. 433, pl. 20, figs, 2a, b.

This species is rare in the Portsmouth area. It appears to have a widespread distribution.

Family REOPHACIDAE

HORMOSINA sp.

(Plate 1, figures 8, 9)

I have not been able to find this species in the literature, but have insufficient material to make an adequate study of it. It is very small, 0.28–0.6 mm. in length, usually composed of three to four chambers, the early chambers being globular, the last more elongate. It occurs only rarely in the Portsmouth area.

REOPHAX ARCTICA H. B. Brady

(Plate 1, figures 6, 7)

Reophax arctica H. B. Brady, 1881, Ann. Mag. Nat. Hist., ser. 5, vol. 8, p. 405, pl. 21, fig. 2.

Bigenerina arctica Cushman (part) 1948, Spec. Publ. 23, Cushman Lab. Foram. Res., p. 31, pl. 3, fig. 9 (not figs. 10, 11).

Examination of specimens by transmitted light shows that this species is uniserial throughout. Cushman's plesiotypes figured in his monograph on the Arctic were examined. The first figured specimen (fig. 9) is typical. The other two are unrelated forms. Figure 10 is a small specimen of the new species *Textularia torquata* (q. v.) and figure 11 is apparently an immature form of *Spiroplectammina biformis*.

This species occurs at many stations in the Portsmouth area. It occurs in the Arctic but is not reported from south of Cape Cod.

REOPHAX CURTUS Cushman

(Plate 1, figures 11–19)

Reophax curtus Cushman, 1920, Bull. 104, U. S. Nat. Mus., pt. 2, p. 8, pl. 2, figs. 2, 3.

Reophax scorpiurus Balkwill and Wright (not Montfort), 1885, Trans. Roy. Irish. Acad., vol. 28, Sci., p. 328, pl. 13, figs. 5a, b; Goës (part), 1894, Kongl. Svensk. Vet. Akad. Handl., vol. 25, no. 9, p. 24, pl. 5, figs. 160–167 (?not 158, 159, 168, 169).

?*Reophax subfusiformis* Earland, 1933, Discovery Repts., vol. 7, p. 74, pl. 2, figs. 16–19.

Reophax subfusiformis Höglund, 1947, Zool. Bidrag från Uppsala, bd. 26, p. 82, pl. 9, figs. 1–4; pl. 26, figs. 1–36; pl. 27, figs. 1–19; text figs. 43–50.

Reophax cf. *pilulifer* Cushman (not H. B. Brady), 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 10, pl. 1, fig. 21.

The holotype has not been seen, but from material at hand from the Gulf of Maine, where Cushman has reported the species, its characteristics can be studied. The species is a very variable one. Many specimens can be found without a neck, as described by Cushman. Many others, however, have a neck which is composed of fine material and is probably easily broken. Specimens occur with from three to five, or even six, chambers, although the majority have four. The relative size of the last chamber varies, the chambers in some specimens increasing much more gradually in size than in others. The specimens with chambers increasing most rapidly in size are usually the larger forms having very large proloculi and probably represent the megalospheric generation. It is apparently specimens of this type that Cushman used to illustrate the species.

Until Earland's specimens from the Antarctic can be seen, his species *R. subfusiformis* cannot be definitely placed in the synonymy under *R. curtus*, but it seems probable that it should be. The main difference between the two species as described and figured, aside from the presence of a neck and the number of chambers, is in the character of the wall. The holotype of *R. curtus* has a very rough, coarsely arenaceous wall. Earland's species is described as having a wall that is "thin and smoothly finished externally". In the Gulf of Maine there is a relatively small number of specimens having such a wall. One of these forms is figured (pl. 1, fig. 17). Whether or not this is a separate species or even a variety is very questionable. It is identical with the specimens of typical *R. curtus* in every other respect. Höglund's Swedish species appears to be identical with Cushman's although I have not examined specimens.

Specimens occur which are very similar to the species from Vineyard Sound referred to *R. scorpiurus?* by Cushman (1944, p. 10). The chambers increase much more slowly in size as added, but are inflated. In the ecologic study of the Portsmouth area these forms have been combined with *R. curtus* to which they appear to be closely related (pl. 1, figs. 15, 16, 18). A second form, which I am at present regarding as a variant of *R. curtus*, is very small, with uninflated chambers and a prolonged neck (pl. 1, fig. 19). It is usually associated with the typical form, but is very rare and it has been impossible to obtain enough material for study.

REOPHAX GRACILIS (Kiaer)

(Plate 2, figure 1)

Nodulina gracilis Kiaer, 1900, Rept. Norwegian Fish Mar. Invest., vol. 1, no. 7, p. 24, 2 text figs. (the left-hand one is questionable).

This species is very rare in the Portsmouth area. It is not reported elsewhere in the western Atlantic.

REOPHAX SCOTTII Chaster

(Plate 2, figure 2)

Reophax scottii Chaster, 1890–91 (1892), First Rept. Southport Soc. Nat. Sci., p. 57, pl. 1, fig. 1.

Reophax catella Höglund, 1947, Zool. Bidrag från Uppsala, bd. 26, p. 97, text figs. 77, 78.

This species is present at a number of stations in the Portsmouth area. Höglund (1947, p. 11) has wrongly interpreted the species because of having no access to Chaster's original description. He based his interpretation of the species on Cushman's (1920, p. 11) description which also appears to be in error. The original description is given here for the benefit of those who have not seen it. "Test elongate, narrow, composed of a large number (10–20) of segments which gradually increase in size; segments generally somewhat pyriform, and abruptly truncate below; aperture small; texture very delicate and transparent, the test being built up of thin scales of mica or other material neatly joined at their margins by chitinous material. The test when moist is quite flexible. Length .4–.625 mm." There is no mention of compression of the test as asserted by Cushman and later by Höglund nor of a wall composed of mica flakes "imbricately attached to a chitinous membrane" as described by Höglund. Höglund's *R. catella* seems to be identical with Chaster's form.

The species has been observed in Buzzards Bay and Long Island Sound south of Cape Cod but is not reported from the Arctic.

Family AMMODISCIDAE

AMMODISCUS CATINUS Höglund

(Plate 2, figures 3, 4)

Ammodiscus catinus Höglund, 1947, Zool. Bidrag från Uppsala, bd. 26, p. 122, pl. 8, figs. 1, 7; pl. 28, figs. 19–23; text. figs. 82–84, 105–107, 109.

This species is widespread in the Portsmouth area. Its concavo-convex character and narrow whorls distinguish it easily from the following species. It is reported only from the Swedish areas studied by Höglund.

AMMODISCUS MINUTISSIMUS Cushman and McCulloch

(Plate 2, figure 5)

Ammodiscus minutissimus Cushman and McCulloch, 1939, Allan Hancock Pacific Exped., vol. 6, p. 70, pl. 5, figs. 3, 4.

The Portsmouth specimens apparently are identical with the types examined at the Cushman Laboratory. The original description also seems to agree in all respects. This species is reported by Cushman (1944, p. 11) from shallow water, 18–33 m., in this area and at a few localities south of Cape Cod at 11 m. and 15 m.

GLOMOSPIRA GORDIALIS (Jones and Parker)

(Plate 2, figure 6)

Trochammina squamata var. *gordialis* Jones and Parker, 1860, Quart. Jour. Geol. Soc., vol. 16, p. 304; Parker and Jones, 1865, Phil. Trans. Roy. Soc. London, vol. 155, p. 408, pl. 15, fig. 32.

This species is rare.

Family LITUOLIDAE

AMMOBACULITES CASSIS (Parker)

(Plate 2, figures 8–10)

Lituola cassis Parker, 1870, in Dawson, Canadian Nat., n. ser., vol. 5, pp. 177, 180, fig. 3.

This species was named from specimens collected in Gaspé Bay, Gulf of St. Lawrence. It shows its best development in the Arctic.

Portsmouth specimens are less broad and more elongate, the chambers not extending so far down on the inner side, although steeply slanting as in normal specimens. In spite of these differences there seems no doubt that the specimens should be referred to Parker's species. It is suggested that this abnormal variation may be caused by minimum conditions for survival of the species obtaining in the Portsmouth area. It is not found farther south than Massachusetts Bay where it shows similar variations with even greater elongation of the test.

HAPLOPHRAGMOIDES BRADYI (Robertson)

(Plate 2, figure 11)

Trochammina robertsoni Brady, 1887 (not Brady, 1876), Jour. Roy. Micr. Soc., p. 893.

Trochammina bradyi Robertson, 1891, Ann. Mag. Nat. Hist., ser. 6, vol. 7, p. 388.

This species is fairly abundant in deeper parts of the Portsmouth area. It has been observed east of Cape Cod at stations deeper than 85 m. (Parker, 1948) but is not reported elsewhere in the western Atlantic, although it is found farther south in the Gulf of Mexico.

HAPLOPHRAGMOIDES GLOMERATUS (H. B. Brady)

(Plate 2, figures 13, 14)

Lituola glomerata H. B. Brady, 1878, Ann. Mag. Nat. Hist., ser. 5, vol. 1, p. 433, pl. 20, figs. 1a-c.

This species is widespread in the Portsmouth area. It is not found on the continental shelf south of Cape Cod, although, like the previous species, it is found in the Gulf of Mexico. It also occurs abundantly in the Arctic.

LABROSPIRA ARCTICA n.sp.

(Plate 2, figures 7, 12)

Trochammina trullissata H. B. Brady (part) (not H. B. Brady, 1879, Quart. Jour. Micr. Sci., vol. 19 (n.s.), no. 73, p. 56, pl. 5, figs. 10a, b, 11), 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 342, pl. 40, figs. 14a, b (not figs. 13a, b, 15, 16).

Test small, compressed, partially evolute; periphery rounded, slightly lobulate; chambers 6–7 in the adult whorl, slightly inflated;

sutures straight, slightly depressed; wall very smooth, polished, finely arenaceous; aperture small, narrow, slightly curved, with a broad protuberant lip. Maximum diameter 0.4 mm., maximum thickness 0.11 mm.

Holotype from station 12, Baffin Bay at a depth of 629 m.; Lat. 74°46′N., Long. 74°25′W.

This species differs from other described species such as *L. jeffreysii* in the smooth, highly polished wall. It also differs from *L. jeffreysii* in the more regular, less lobulate periphery, straighter sutures, and smaller size. It has the same type of wall as *Haplophragmoides bradyi* and this feature makes it very distinctive. It has been observed only in samples from Baffin Bay, from water depths greater than 250 m. It is of interest to note that figures 10a, b of *Trochammina trullissata* Brady 1879 are identical with the CHALLENGER Report figures, pl. 40, figs. 13a, b, which Cushman (1910, p. 113, text figs. 174a, b) renamed *Cyclammina bradyi*. This form should, therefore, retain the specific name *trullissata*. Brady's figure 11 of 1879 is a section which was not reproduced in the CHALLENGER Report and apparently represents a *Haplophragmoides*. Whether or not this figure represents the same species as his figures 10a, b is somewhat questionable and the genus may be referable to *Cyclammina* as stated by Cushman.

LABROSPIRA CRASSIMARGO (Norman)

(Plate 2, figures 16a, b)

Haplophragmium crassimargo Norman, 1892, Mus. Normanianum, pt. 8, p. 17.

Haplophragmium canariense Brady (part) (not d'Orbigny), 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 310, pl. 35, fig. 4 (not figs. 1–3, 5).

Haplophragmoides major Cushman, 1920, Bull. 104, U. S. Nat. Mus., pt. 2, p. 39, pl. 8, fig. 6.

Labrospira crassimargo Höglund, 1947, Zool. Bidrag från Uppsala, bd. 26, p. 141, pl. 11, fig. 1; text figs. 121–125.

Study of a paratype specimen of *Haplophragmoides major* at the Cushman Laboratory shows it to have the "intereo-areal" aperture designated by Höglund (1947, p. 141) as the distinguishing characteristic of the genus *Labrospira*. Since, as Höglund points out (1947, p. 143), Cushman's characterization of the aperture of *H. major* as "an elongate semicircular slit at the base of the final chamber, the upper portion forming a thin lip" is the only apparent basis for a separation of this form from Norman's, the two species would seem to be synonymous. I have compared the paratype specimens with Arctic specimens from Greenland as well as with the Portsmouth forms and all appear to be identical. As Höglund points out, the detection of the presence of the lower lip is sometimes difficult.

There is a possibility that d'Orbigny incorrectly analyzed the character of the aperture of *Haplophragmoides canariensis* (*Nonionina canariensis* d'Orbigny, 1839, in Barker-Webb and Berthelot, Hist. Nat. Iles Canaries, vol. 2, pt. 2, "Foraminifères," p. 128, pl. 2, figs. 33, 34) which was designated by Cushman as the genotype of *Haplophragmoides* (1910, p. 99). A study of material from the Canary Islands or of type material (if possible) should clarify this point and is necessary to determine the final validity of Höglund's genus.

This species is very common in the Portsmouth area. It is found at shallow depths (15 m.–90 m.) but occurs only rarely in the area farther south (Parker, 1948, p. 222). It is common in the Arctic.

LABROSPIRA JEFFREYSII (Williamson)

(Plate 2, figures 15, 17–20)

Nonionina jeffreysii Williamson, 1858, Rec. Foram. Great Britain, p. 34, pl. 3, figs. 72, 73.

Haplophragmoides columbiensis Cushman 1944, (not Cushman, 1925), Spec. Publ. 12, Cushman Lab. Foram. Res., p. 11, pl. 2, fig. 1; Parker, 1948, Bull. Mus. Comp. Zoöl., vol. 100, no. 2, p. 238, pl. 4, fig. 17.

The Portsmouth specimens are somewhat larger than those described by Williamson, with a diameter up to 0.83 mm., and have 6–7 chambers in the adult whorl rather than 7–8 as described by him. In other respects the two species appear to be identical. *H. columbiensis* (Cushman) has a more smoothly polished surface and more flexuose sutures. There is considerable variation in the amount of involution.

This species is widespread in the Portsmouth area, usually occurring at low frequencies. It is found east of Cape Cod but is not reported farther south. Similar specimens occur in the Arctic.

LABROSPIRA cf. NITIDA (Goës)

(Plate 2, figures 21, 22)

Haplophragmium nitidum Goës, 1896, Bull. Mus. Comp. Zoöl., vol. 29, p. 30, pl. 3, figs. 8, 9.

The tests of the Portsmouth specimens do not appear to be as finely arenaceous or as polished as those of Goës's Caribbean form. They are more smoothly finished and have a more polished surface, however, than such forms as *L. crassimargo*. The species is very rare in this area and has not hitherto been reported in the western Atlantic north of South Carolina.

RECURVOIDES TURBINATUS (H. B. Brady)

(Plate 2, figures 23, 24)

Haplophragmium turbinatum H. B. Brady, 1881, Quart. Jour. Micr. Sci., n. s., vol. 21, p. 50; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 312, pl. 35, figs. 9a-c.

This species seems to fit Brady's description and figures very well, the only apparent discrepancy being in size. The Portsmouth specimens attain a maximum diameter of 0.4 mm. Brady describes specimens up to 0.75 mm. Brady describes the species as having six chambers in the final whorl which is true also of the Portsmouth specimens. Cushman (1920, pp. 81, 82) says that it may have up to eight chambers. It seems probable that he has confused Brady's form with another, possibly *R. contortus* Earland, or that he has included more than one species under this name. Höglund's species *R. trochamminiformis* (1947, p. 149) also shows some resemblance to this species but apparently has somewhat more inflated chambers. It is possible, though, that it should be placed in the synonymy under this species.

The species is a very common one in the Portsmouth area and has also been observed at stations in the vicinity of Greenland. It is reported by Parker (1948, p. 238) from the continental shelf east of Cape Cod.

Family TEXTULARIIDAE

SPIROPLECTAMMINA BIFORMIS (Parker and Jones)

(Plate 3, figures 1, 2)

Textularia agglutinans d'Orbigny var. *biformis* Parker and Jones, 1865, Phil. Trans. Roy. Soc. London, vol. 155, p. 370, pl. 15, figs. 23, 24.

Spiroplectammina sp. Parker, 1948, Bull. Mus. Comp. Zoöl., vol. 100, no. 2, p. 239, pl. 4, fig. 21.

This species is common at many stations. There is a good deal of size variation in the specimens from different stations. Microspheric specimens vary from 0.07–0.14 mm. in width and 0.25–0.54 mm. in length; megalospheric individuals from 0.11–0.14 mm. in width and 0.21–0.36 mm. in length. I have seen specimens from off Greenland with a maximum length of 0.65 mm. and maximum width of 0.21 mm. This species is recorded by Cushman (1944, p. 13) from just south of Cape Cod.

SPIROPLECTAMMINA TYPICA Lacroix

(Plate 3, figures 3–8)

Spiroplectammina typica Lacroix, 1931, Bull. Instit. Ocean., Monaco, no. 582, p. 14, fig. 9; 1932, ibid, no. 591, p. 6, text figs. 2, 3.

The specimens from the Portsmouth area are larger than those figured by Lacroix. His specimens, figured in 1932, are approximately 0.22 mm. and 0.13 mm. in length and 0.08 mm. and 0.06 mm. in width. The Portsmouth specimens have a maximum length of 0.65 mm. and maximum width of 0.25 mm. In other respects the forms seem to be identical. This size discrepancy is a large one but it does not give a sufficient basis for the erection of a new species. *S. typica* is a much more compressed form than *S. biformis*. It has been reported previously only from the Mediterranean.

TEXTULARIA TORQUATA n.sp.

(Plate 3, figures 9–11)

Bigenerina arctica Cushman (part) (not H. B. Brady), 1948, Spec. Publ. 23, Cushman Lab. Foram. Res., p. 31, pl. 3, fig. 10 (not figs. 9, 11).

Test small, compressed and frequently somewhat twisted, rapidly tapering from the broadest part near the apertural end; periphery slightly lobulate due to the overlapping of the chambers; chambers 5–6 pairs in the biserial portion, slightly inflated; sutures slightly depressed, slanting downward at an angle of about 45°; wall rough, coarsely arenaceous; aperture narrow, loop-shaped, extending up into the apertural face almost to the apex of the test. Maximum length 0.29 mm., maximum width 0.15 mm., maximum thickness 0.07 mm.

Holotype from station 114 at a depth of 93 m., Lat. 42°45.7′N, Long. 70°29.3′W.

This species most closely resembles *T. contorta* Höglund but differs in having clearly visible, somewhat depressed sutures; in the aperture which is an elongate loop instead of horseshoe-shaped; and in the fact that many individuals show a definite coil at the initial end.

This species is widespread in the Portsmouth area and is found off Greenland where it has been observed in samples from Baffin Bay and the Kane Basin.

Family VALVULINIDAE

EGGERELLA ADVENA (Cushman)

(Plate 3, figures 12, 13)

Verneuilina advena Cushman, 1921 (1922), Contr. Canadian Biol., no. 9, p. 141.
Verneuilina polystropha Cushman (not Reuss), 1920, Rept. Canadian Arctic Exped., vol. 9, pt. M, p. 8, pl. 1, fig. 5.
Eggerella arctica Höglund, 1947, Zoöl. Bidrag från Uppsala, bd. 26, p. 193, pl. 16, fig. 4; text figs. 166–168.

This species was first referred to *Verneuilina polystropha* Cushman, 1920, as pointed out by Cushman (1948, p. 32). The fact that he also included a reference to *V. polystropha* Heron-Allen and Earland, 1913, in a later paragraph does not alter the fact that the Arctic specimens should form the basis for the conception of the species. The specimen figured by Cushman in 1920 is 0.42 mm. long. Oddly enough the drawing shows a hint of multiple chambers in the initial portion of the test although Cushman described it originally as triserial throughout. The species is common in the Portsmouth area. It occurs on the continental shelf south of Cape Cod at depths of less than 90 m. (Parker, 1948, p. 221) and is also found in the Arctic.

VALVULINA CONICA Parker and Jones

(Plate 3, figures 14, 18)

Valvulina triangularis d'Orbigny var. *conica* Parker and Jones, 1865, Phil. Trans. Roy. Soc. London, vol. 155, p. 406, pl. 15, fig. 27.
Valvulina triangularis Parker and Jones (not d'Orbigny), 1857, Ann. Mag. Nat. Hist., ser. 2, vol. 19, p. 23 (295), pl. 11, figs. 15, 16.

This species is found in small percentages at many stations. South of Cape Cod it is found in the deepest facies, 300–680+m., in small numbers (Parker, 1948, p. 226). It occurs as far north as the Gulf of St. Lawrence (Cushman, 1922, p. 62).

Family SILICINIDAE

MILIAMMINA FUSCA (H. B. Brady)

(Plate 3, figures 15, 16)

Quinqueloculina fusca H. B. Brady, 1870, Ann. Mag. Nat. Hist., ser. 4, vol. 6, p. 47 (286), pl. 11, figs. 2a-c, 3.

Quinqueloculina fusca H. B. Brady var. *groenlandica* Cushman 1944 (not Cushman, 1933), Spec. Publ. 12, Cushman Lab. Foram. Res., p. 14, pl. 2, fig. 21.

This species is somewhat more coarsely arenaceous than the other reported species of the genus. In other respects it is typical. There is some variation in size, but the maximum observed length is 0.5 mm. It is found only at nearshore stations in the Portsmouth area. It is reported in England from brackish water near the mouths of rivers and by Phleger and Walton (1950, p. 280) from Barnstable Harbor. The species has also been observed south of Cape Cod in Long Island Sound in brackish and nearshore water. The form from the Arctic figured under this name by Cushman (1948, p. 33, pl. 3, figs. 16, 17) does not belong to this species.

In connection with the study of *M. fusca* at the Cushman Laboratory, specimens of "*Quinqueloculina groenlandica*" Cushman were examined and found to belong to the genus *Miliammina*.

Family MILIOLIDAE

PYRGO SUBSPHAERICA (d'Orbigny)

(Plate 3, figure 17)

Biloculina subsphaerica d'Orbigny, 1839, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 162, pl. 8, figs. 25–27.

This species is rare. It has not been previously reported from north of Cape Cod. It is rare in the facies from 90–300 m. south of Cape Cod (Parker, 1948, p. 224).

QUINQUELOCULINA ARCTICA Cushman

(Plate 3, figures 19a, b)

Quinqueloculina arctica Cushman, 1933, Smithsonian Misc. Coll., vol. 89, no. 9, p. 2, pl. 1, figs. 3a-c.

Typical specimens occur in the Portsmouth area. A few reach a length of 1.0 mm. although Cushman gives the maximum length of Arctic specimens as 0.65 mm. (Cushman, 1948, p. 35). The species is not common but is of interest as being the first noted occurrence south of the Arctic. A few specimens have been observed south of Cape Cod near Block Island.

QUINQUELOCULINA FRIGIDA n.sp.

(Plate 3, figures 20a, b)

Test medium in size, periphery rounded but not broad; chambers protruding on the four-chambered side but with rounded angles, the center chamber on the three-chambered side narrow, in a concave area formed by the outer chambers; wall somewhat rough, the outer layer formed of medium-sized sand grains set in a ferruginous calcareous cement; aperture rounded on a slightly projecting neck, with a simple tooth. Maximum length 0.8 mm.; maximum width 0.6 mm.; maximum thickness 0.4 mm.

Holotype from station 610 at a depth of 37 m.; Lat. 43°04.6′N, Long. 77°33.6′W.

This species somewhat resembles *Q. agglutinata* Cushman, which was described from off Alaska. It is smaller and the chambers are less sharply angled and much narrower at the outer periphery making the test less thick in proportion to the width. Cushman described *Q. agglutinata* (1917, p. 43) as 0.9 mm. in length but specimens have been observed from Dundas Harbor, near Greenland, more than 1.0 mm. in length. *Q. frigida* occurs at several stations in the Portsmouth area but is not abundant.

QUINQUELOCULINA SEMINULA (Linné)

(Plate 3, figures 21a, b, 22a, b; pl. 4, figures 1, 2)

Serpula seminulum (Linné), 1758, Syst. Nat., ed. 10, p. 786.

This species is rare. It is apparently more common at Cushman's shallow water stations in the Gulf of Maine (Cushman, 1944, p. 13). On the continental shelf south of Cape Cod it is found in the facies from 15–90 m. (Parker, 1948, p. 221). It is also reported from the Arctic.

QUINQUELOCULINA SUBROTUNDA (Montagu)

(Plate 4, figures 4a, b)

"Serpula subrotunda dorso elevato" Walker and Boys, 1784, Test. Min., p. 2. pl. 1, fig. 4.

Vermiculum subrotundum Montagu, 1803, Test. Brit., pt. 2, p. 521.

Vermiculum disciforme Macgillivray, 1843, Hist. Moll. Anim. Aberdeen, p. 319.

Miliolina seminulum (Linné) var. *disciformis* Williamson, 1858, Rec. Foram. Great Britain, p. 86, pl. 7, figs. 188, 189.

Occasional specimens are seen with *Massilina*-like chambers as pointed out by Cushman (1948, p. 35). This characteristic and the character of the aperture make the inclusion of the species in the genus *Quinqueloculina* somewhat questionable. It is reported from the Arctic and also occurs south of Cape Cod. It is rare in the Portsmouth area. Many forms referred to "*Quinqueloculina secans* d'Orbigny" and "*Triloculina circularis* Bornemann" in the literature may be referable to *Q. subrotunda*.

TRILOCULINA TRICARINATA d'Orbigny

(Plate 4, figure 5)

Triloculina tricarinata d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 299, no. 7; Modèles no. 94.

The Portsmouth specimens are slightly more rounded at the periphery than d'Orbigny's model. The species is rare. It is difficult to get accurate information on its distribution elsewhere in the western Atlantic although Parker (1948, p. 227) reports it as rare south of Cape Cod in her deepest facies at 300–680 m. It is also reported from the Arctic but the reliability of these reports is doubtful.

Family TROCHAMMINIDAE

TROCHAMMINA ADVENA Cushman

(Plate 4, figures 3a, b)

Trochammina advena Cushman, 1922, Carnegie Instit. Washington, Publ., p. 20, pl. 1, figs. 2–4.

?*Trochammina* cf. *rotaliformis* Höglund, 1947 (not Wright, 1911), Zoöl. Bidrag från Uppsala, bd. 26, p. 198, pl. 17, figs. 1, 2; text figs, 180, 181.

This species is found in small numbers at many stations. It is identical with Cushman's species except for a slightly greater inflation of the chambers. It is reported from the Tortugas region off Florida, from the Gulf of Mexico and as *T. globulosa* Cushman, by Parker (1948, p. 240) from the continental shelf east of Cape Cod.

TROCHAMMINA INFLATA (Montagu)

(Plate 4, figures 6, 10)

Nautilus inflatus Montagu, 1808, Test. Brit., Suppl., p. 81, pl. 18, fig. 3.

The specimens from the Portsmouth area are small but otherwise typical. They are found only at nearshore stations. The species is found south of Cape Cod but is not reported from the Arctic.

TROCHAMMINA LOBATA Cushman

(Plate 4, figures 7a, b)

Trochammina lobata Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 18, pl. 2, fig. 10.

This species was described from the Gulf of Maine. It also occurs south of Cape Cod at depths shallower than 90 m. (Parker, 1948, p. 221).

TROCHAMMINA MACRESCENS H. B. Brady

(Plate 4, figures 8a, b)

Trochammina inflata (Montagu) var. *macrescens* H. B. Brady, 1870, Ann. Mag. Nat. Hist., ser. 4, vol. 6, p. 51, pl. 11, figs. 5a-c.

This species is rare at two shallow stations. It also occurs in brackish water in Long Island Sound. The species reported by Phleger and Walton (1950, p. 280) from Barnstable Harbor, north of Cape Cod, should be referred to *Jadammina polystoma* Bartenstein and Brand. The two forms appear to be distinct and have not been found together at the same locality.

TROCHAMMINA QUADRILOBA Höglund

(Plate 4, figures 9a, b)

Trochammina quadriloba Höglund, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 2, p. 46.

Trochammina pusilla Höglund, 1947 (not Geinitz, 1848), Zoöl. Bidrag från Uppsala, bd. 26, p. 201, pl. 17, figs. 4a-c; text figs. 183, 184.

This species appears to be identical with Höglund's. It is rare at many stations. The species has also been observed in material from Lancaster Sound, off Greenland. It has not been previously reported except by Höglund in his Swedish material.

TROCHAMMINA SQUAMATA Parker and Jones and related species

(Plate 4, figures 11–16)

Trochammina squamata Parker and Jones, 1865, Phil. Trans. Roy. Soc. London, vol. 155, p. 407, pl. 15, figs. 30, 31a-c.

T. squamata and its allied species are treated as a unit in analyzing the faunal distribution. This is done because of the difficulty of differentiating the forms in counting without causing great delay. Since they usually appear to act as a faunal unit it does not seem worthwhile to attempt a separation. Some of the species of this group, which are represented, are: the typical species (pl. 4, figs. 11, 12) which seems to be identical with "*T. propria* Cushman" (1944, p. 19, pl. 2, fig. 11); *T. ochracea* (Williamson) (*Rotalina ochracea* Williamson, 1858, p. 55, pl. 4, fig. 112; pl. 5, fig. 113) (pl. 4, figs. 13, 14); and *T.* (*Remaneica*) *helgolandica* Rhumbler (1938, p. 195, figs. 38–45) (pl. 4, figs. 15, 16).

Representatives of this group are found in the Arctic and in shallow water samples south of Cape Cod. They are widespread in the Portsmouth area.

TROCHAMMINELLA ATLANTICA n.sp.

(Plate 4, figures 17a, b, 18, 19)

Test small, slightly compressed, with a low trochoid spire; periphery rounded, very lobulate; chambers 5–6 in the adult whorl, more commonly 5, inflated, especially toward the outer part; sutures distinct, depressed, slightly curved; wall thin, slightly rough, composed of medium sand grains of varying size; aperture an elongate slit near the inner margin of the chamber, with a distinct lip. Maximum diameter 0.47 mm., maximum thickness 0.22 mm.

Holotype from Core 16, Melville Sound, off Canada, at 124 m., Lat. 74°34′N, Long. 110°40′W.

This species is often found associated with *T. bullata* Höglund but may be distinguished easily by its somewhat larger size, lower spire and more numerous, less globose chambers. Some specimens appear distorted owing to the uneven inflation of the chambers. Except for the character of the aperture the species shows a rather close resemblance to *Trochammina advena* Cushman.

Family LAGENIDAE

OOLINA COSTATA (Williamson)

(Plate 4, figures 20, 21)

Entosolenia costata Williamson, 1858, Rec. Foram. Great Britain, p. 9, pl. 1, fig. 18.

Lagena costata Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 21, pl. 3, fig. 4.

O. costata is not reported elsewhere in the western Atlantic. A few specimens have been observed in material from off Greenland.

Family POLYMORPHINIDAE

PSEUDOPOLYMORPHINA NOVANGLIAE (Cushman)

(Plate 5, figure 1)

Polymorphina lactea (Walker and Jacob) var. *novangliae* Cushman, 1923, Bull. 104, U. S. Nat. Mus., pt. 4, p. 146, pl. 39, figs. 6–8.

This species was described from the Gulf of Maine. It is found south of Cape Cod and is reported from Gaspé Bay.

Family NONIONIDAE

ASTRONONION STELLATUM Cushman and Edwards

(Plate 5, figures 2, 3)

Nonionina elegans d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 294, no. 10 (nomen nudum).
Fornasini, 1899 (not Williamson, 1858), Mem. Accad. Sci. Bologna, ser. 5a, vol. 7, p. 655, fig. 5.
Nonionina stelligera d'Orbigny (part) of authors.
Astrononion stellatum Cushman and Edwards, 1937, Contr. Cushman Lab. Foram. Res., vol. 13, pt. 1, p. 32, pl. 3, figs. 9–11.
Astrononion stelligerum Cushman, 1948 (not d'Orbigny, 1839), Spec. Publ. 23, Cushman Lab. Foram. Res., p. 55, pl. 6, fig. 6.

d'Orbigny's species was based on specimens collected from "le banc de 'Terre-Neuve' "; since there is no accompanying designation it is a *nomen nudum.* Fornasini's figure, one of d'Orbigny's unpublished figures, shows the species to be identical with *Astrononion stellatum* Cushman and Edwards described from off southern Iceland. The latter name stands owing to the appearance of Williamson's "*Nonionina*" *elegans* before Fornasini's publication of the figure of d'Orbigny's species. The species bears a close resemblance to the Mediterranean form *Astrononion stelligerum* (d'Orbigny) but is more compressed and has a more lobulate periphery caused by the greater inflation of the chambers. It commonly has 7–8 chambers although occasional specimens have more.

The species has not been found south of Cape Cod in the western Atlantic.

ELPHIDIUM ADVENUM (Cushman) var. MARGARITACEUM Cushman

(Plate 5, figure 4)

Polystomella advenum Cushman var. *margaritaceum* Cushman, 1930, Bull. 104, U. S. Nat. Mus., pt. 7, p. 25, pl. 10, fig. 3.

This species is very rare in the Portsmouth area. On the continental shelf south of Cape Cod it is reported in shallow water samples by Cushman (1944, p. 26).

ELPHIDIUM ARTICULATUM (d'Orbigny)

(Plate 5, figures 5–7)

Polystomella articulata d'Orbigny, 1839, Voy. Amér. Mérid., vol. 5, pt. 5, "Foraminifères," p. 30, pl. 3, figs. 9, 10.

Nonion orbiculare Cushman (not H. B. Brady), 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 24, pl. 3, fig. 24.

A comparison with specimens from the Falkland Islands, one of the localities from which d'Orbigny described the species, shows the Portsmouth species to be almost identical although slightly less compressed. Specimens are found with opaque and translucent tests, the latter being the forms which Cushman called *N. orbiculare* in this area. His plesiotype of this form was studied and found to be different from the plesiotype of *N. orbiculare* from the Arctic (Cushman, 1948, pl. 6, fig. 3). The retral processes, though present in the translucent forms, are much less prominent. This feature may be observed in other species of *Elphidium*, notably *E. incertum*, where a superficial examination of a large group of specimens has suggested that several species are present depending on the degree of translucence of the test. *E. articulatum* has the supplementary apertures on the apertural face characteristic of *Cribroelphidium* Cushman and Bronnimann. They appear in varying degree in many species of *Elphidium* and if a division of the genus on this basis is necessary, as seems improbable, it should more appropriately appear as a subgeneric one.

E. articulatum appears to be closely related to *E. bartletti* Cushman. The adult forms of the latter species have a maximum of 12 chambers instead of the 10 or less of the former. The young specimens of *E. bartletti*, however, appear to be identical with *E. articulatum*. It is possible that *E. bartletti* represents the Arctic development of *E. articulatum*, which is not reported from that area.

ELPHIDIUM EXCAVATUM (Terquem)

(Plate 5, figure 8)

Polystomella excavata Terquem, 1875, Essai Class. Anim. Dunkerque, pt. 1, p. 25, pl. 2, figs. 2a-f.

The few specimens found are very similar to specimens at the Cushman Laboratory from Bognor, England. The species is reported from shallow waters north of Cape Cod by Cushman (1944, p. 26). It also occurs south of Cape Cod in the Long Island Sound-Buzzards Bay area.

ELPHIDIUM INCERTUM (Williamson) var. CLAVATUM Cushman

(Plate 5, figures 10, 11)

Elphidium incertum (Williamson) var. *clavatum* Cushman, 1930, Bull. 104, U. S. Nat. Mus., pt. 7, p. 20, pl. 7, figs. 10a, b.

This variety is the commonest form of Williamson's species found in the Portsmouth area. It is variable, however, and some specimens may not belong to the variety. Most of the specimens have a ventral plug or plugs of varying size which do not appear in Williamson's figure or description. South of Cape Cod in the shallow water of Long Island Sound and nearby bays the species is even more variable. *E. incertum* and variants are reported in the western Atlantic from the coast of Maryland to the Arctic.

ELPHIDIUM SUBARCTICUM Cushman

(Plate 5, figure 9)

Elphidium subarcticum Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 27, pl. 3, figs. 34, 35.
Nonion pauciloculum Cushman, *ibid.*, p. 24, pl. 3, fig. 25.

This species is very common. It shows the same variable characteristics of the other species of this genus. The sutures, though typically not depressed, sometimes appear as sharp, deep incisions where the amorphous material usually filling in the area is absent. The retral processes are frequently concealed by this amorphous material and it is specimens of this type which Cushman calls by the name *Nonion pauciloculum.* A study of large suites of specimens, however, shows that this species cannot be isolated. Retral processes could be observed in autotypes kindly furnished by Cushman.

Stunted specimens with four or five chambers have been observed from nearshore stations in Long Island Sound and Massachusetts Bay, apparently living at the minimum conditions for survival. This form is widespread on the continental shelf south of Cape Cod and is also found in the Arctic.

NONION LABRADORICUM (Dawson)

(Plate 5, figure 12)

Nonionina labradorica Dawson, 1860, Canadian Nat., vol. 5, p. 191, fig. 4.

This species occurs in its typical form. Its range extends northward to the Arctic but it is not found south of Cape Cod.

NONIONELLA AURICULA Heron-Allen and Earland

(Plate 5, figures 13a, b, 14a, b)

Nonionella auricula Heron-Allen and Earland, 1930, Jour. Roy. Micr. Soc., vol. 50, p. 192, pl. 5, figs. 68-70.

The Portsmouth specimens are about twice as large as those described by Heron-Allen and Earland, with a maximum length of 0.5 mm. The species is rare. Cushman (1944, p. 25) reports it from a few stations just south of Cape Cod, although *N. atlantica* seems to be better represented in that area. Similar, though considerably larger, specimens have been observed in the Arctic.

NONIONELLA TURGIDA (Williamson) var. DIGITATA Nφrvang

(Plate 5, figures 15, 16)

Nonionella turgida (Williamson) var. *digitata* Nørvang, 1945, Zoöl. Iceland, vol. 2, pt. 2, Foraminifera, p. 29, text. fig. 4.

This variety is very rare. The only previous report is by Nφrvang from off Iceland in 141 m.

Family BULIMINIDAE

ANGULOGERINA ANGULOSA (Williamson)

(Plate 5, figures 18, 19)

Uvigerina angulosa Williamson, 1858, Rec. Foram. Great Britain, p. 67, pl. 5, fig. 140.

Most of the specimens are smaller and less sharply angled than those seen from the vicinity of Ireland. At some stations, however, larger, more typical specimens are found. South of Cape Cod it is not found shallower than 63 m. (Parker, 1948). Cushman (1944, p. 30) reports it from shallow areas in the Gulf of Maine from 18 m. to 33 m., but it is found only rarely in the Portsmouth area.

Bolivina pseudoplicata Heron-Allen and Earland

(Plate 5, figure 17)

Bolivina pseudoplicata Heron-Allen and Earland, 1930, Jour. Roy. Micr. Soc., vol. 50, p. 81, pl. 3, figs. 36–40.

This species is rare in the Portsmouth area. It is apparently found only in shallow water of less than 90 m. as reported by Cushman (1944, p. 29) and Parker (1948, p. 221). The same is true of most of the reported occurrences around the British Isles although in the vicinity of Sweden Höglund reports its greatest frequency at 200 m. in the Skagerak (Höglund, 1947, p. 263).

Bolivina pseudopunctata Höglund

(Plate 5, figures 20, 21)

Bolivina pseudopunctata Höglund, 1947, Zoöl. Bidrag från Uppsala, bd. 26, p. 273, pl. 24, fig. 5; pl. 32, figs. 23, 24; text figs. 280, 281, 287.

This species is rare. It does not exceed the 0.4 mm. length described by Höglund as typical. Larger specimens have been seen from the vicinity of Greenland, where the species is found in greater abundance. It has not been observed elsewhere in the western Atlantic.

Bolivina subaenariensis Cushman

(Plate 5, figure 22)

Bolivina subaenariensis Cushman, 1922, Bull. 104, U. S. Nat. Mus., pt. 3, p. 46, pl. 7, fig. 6.

The species is rare in the Portsmouth area, being more common in the deeper water of the area. South of Cape Cod it does not occur in the percentage counts shallower than 114 m. (Parker, 1948, p. 225).

BULIMINA ACULEATA d'Orbigny

(Plate 5, figures 23–25)

Bulimina aculeata d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 269, no. 7; — Fornasini, 1901, Mem. Accad. Sci. Bologna, ser. 5, vol. 9, p. 373, text. fig. 4.

Polymorpha pineiformia Soldani (part), 1791, Testacea, vol. 1, pt. 2, p. 118, pl. 127, fig. 1?; pl. 130, fig. *vv*.

Bulimina pupoides d'Orbigny var. *spinulosa* Williamson, 1858, Rec. Foram. Great Britain, p. 62, pl. 5, fig. 128.

This species varies considerably in the amount of ornamentation. Some forms are almost smooth while others have well-developed spines at the initial portion of the test and occasional spines at the margins of the chambers which sometimes overhang slightly. There is no sharp undercutting at the margins of the chambers as in *B. marginata* d'Orbigny. South of Cape Cod *B. marginata* reaches its peak of frequency at shallower depths than *B. aculeata*. There seems to be no evidence in these localities for the combining of the two species advocated by Höglund (1947, p. 227). *B. aculeata* in the Portsmouth area has a maximum length of 0.54 mm. (excluding the basal spines).

BULIMINA MARGINATA d'Orbigny

(Plate 5, figure 26)

Bulimina marginata d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 269, no. 4, pl. 12, figs. 10–12.

Bulimina pulchella d'Orbigny, 1839, Voy. Amér. Mérid., vol. 5, pt. 5, "Foraminifères," p. 50, pl. 1, figs. 6, 7.

Bulimina serrata Bailey, 1851, Smithsonian Contr., vol. 2, p. 12, pl., figs. 32–34.

This species shows great variation in its character in different parts of the world but is fairly uniform in the Portsmouth area. It is smaller and slightly more spinose than the typical Rimini specimens, never attaining a length greater than 0.5 mm. Similar forms are found along the continental shelf to the south but are distinct from the *B. marginata* var. of Parker (1948, p. 225) found at the outer edge of the shelf. These forms are much more spinose and are distinct from the more typical *B. marginata* which usually attains its greatest frequency at around 100 m. It is possible that a relationship between the deep-water variety and a very spinose form of *B. aculeata*, with which it is frequently associated, might be traced.

BULIMINELLA ELEGANTISSIMA (d'Orbigny)

(Plate 5, figures 27, 28)

Bulimina elegantissima d'Orbigny, 1839, Voy. Amér. Mérid., vol. 5, pt. 5, "Foraminifères," p. 51, pl. 7, figs. 13, 14.

This species is rare in the Portsmouth area. I have observed it in Long Island Sound and Buzzards Bay south of Cape Cod and it is reported from Vineyard Sound by Cushman (1944, p. 27).

GLOBOBULIMINA (DESINOBULIMINA) AURICULATA (Bailey)

(Plate 5, figure 29)

Bulimina auriculata Bailey, 1851, Smithsonian Contr., vol. 2, p. 12, pl., figs. 25–27.

Bulimina pyrula Flint (not d'Orbigny), 1899, U. S. Nat. Mus. Rept., 1897, p. 290, pl. 36, figs. 4, 5.

Höglund (1947, p. 252) places this species in the genus *Globobulimina*. The subgeneric name is retained for this species, which is the subgenotype. Höglund suggests that future revision of this genus may reveal that the subgeneric restriction is unnecessary. If, as he suggests (Höglund, 1947, p. 242), forms like *Bulimina pyrula* d'Orbigny are to be included in the genus, it seems reasonable that forms of the type of Bailey's species should be given subgeneric distinction.

This species is abundant in the Portsmouth area. It occurs also south of Cape Cod at depths greater than 90 m. (Parker, 1948, p. 225). It is replaced in the Arctic by the variety *arctica* named by Höglund (1947, p. 254).

"ROBERTINA" cf. CHARLOTTENSIS (Cushman)

(Plate 5, figures 30a, b)

Cassidulina charlottensis Cushman, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, p. 41, pl. 6, figs. 6, 7.

The species is too rare in this area to identify it with certainty. It appears to resemble closely Höglund's "*Robertina arctica*" d'Orbigny (Höglund, 1947, p. 219). I cannot agree with his interpretation of d'Orbigny's species. An examination of d'Orbigny's figure shows that the aperture extends into the face of the last-formed chamber well above the suture marking the chamber division while in Höglund's species the aperture extends into the chamber from the point of the chamber division. In Höglund's genus *Robertinoides*, on the other hand, the upper part of the main aperture is well up in the upper half of the chamber while the smaller one is at the boundary of the two chamber parts, the so-called "lip" coming in between. This is apparently the case in d'Orbigny's figure although he draws the suture of the division of the chamber and does not indicate the presence of any apertural opening at that point. The specimens assigned to *Robertina arctica* by Cushman and Parker (1947, p. 74) appear to be identical with d'Orbigny's figured form except that there is a narrow apertural opening along the inner part of the chamber division. I believe that it would have been easy for d'Orbigny to overlook this, merely believing it to be a part of the dividing suture. Höglund's detailed study of the two genera is an interesting one and reveals the morphological differences between them. If my interpretation of d'Orbigny's figure is correct Höglund's genus *Robertinoides* should be placed in the synonymy under *Robertina* and a new genus erected for the single-apertured form.

I have observed a single specimen of *R.* cf. *charlottensis* in material from Greenland.

VIRGULINA COMPLANATA Egger

(Plate 6, figures 1a, b, 2a, b)

Virgulina schreibersiana Czjzek var. *complanata* Egger, 1893, Abhandl. k. bayer. Akad. Wiss. München, Cl. 2, bd. 18, p. 292, pl. 8, figs. 91, 92.
Virgulina sp., Parker, 1948, Bull. Mus. Comp. Zoöl., vol. 100, no. 2, p. 240, pl. 5, fig. 14.

The Portsmouth specimens are smaller than those from the Pacific, the longest being about 0.5 mm. They are also somewhat less attenuated than the Pacific specimens. Specimens sent to the Cushman Laboratory by Earland from Drake Strait in the Antarctic are very similar. The species also resembles *V. concava* Höglund, which is perhaps synonymous with Egger's species. The form figured by Cushman from Nigare, Greece (Cushman, 1937, pl. 4, fig. 17 (not figs. 14, 15)), which was examined at the Cushman Laboratory, does not belong to this species.

The species occurs on the continental shelf south of Cape Cod and somewhat more compact specimens have been observed from off Greenland.

VIRGULINA FUSIFORMIS (Williamson)

(Plate 6, figures 3–6)

Bulimina pupoides d'Orbigny var. *fusiformis* Williamson, 1858, Rec. Foram. Great Britain, p. 63, pl. 5, figs. 129, 130.

This species is common in the Portsmouth area. It is found south of Cape Cod and also occurs in material from off Greenland.

Family ROTALIIDAE

DISCORBIS COLUMBIENSIS Cushman

(Plate 6, figures 7a, b, 8a, b, 9a, b)

Discorbis columbiensis Cushman, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, p. 43, pl. 6, figs. 13a-c; Cushman and Todd, 1947, Spec. Publ. 21, Cushman Lab. Foram. Res., p. 20, pl. 3, figs. 14–16.

Discorbis bertheloti (d'Orbigny) var. *floridensis* Cushman, 1944 (not Cushman, 1931), Spec. Publ. 12, Cushman Lab. Foram. Res., p. 31, pl. 4, fig. 17.

Discorbis obtusa Cushman (not *Rosalina obtusa* d'Orbigny), 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 31, pl. 4, fig. 15.

Discorbis subaraucana Cushman 1944 (not Cushman, 1922), Spec. Publ. 12, Cushman Lab. Foram. Res., p. 31, pl. 4, fig. 18.

The Portsmouth specimens appear to be identical with the holotype from Queen Charlotte Sound, British Columbia. They occur only at nearshore stations. In this area they show comparatively little variation or abnormality of growth. Specimens from Long Island Sound, however, vary greatly and show abnormalities similar to those described by Cushman and Todd from Friday Harbor (1947, p. 20, pl. 3, figs. 14–16). These forms may be identical with *Discorbis valvulata* (d'Orbigny). The forms so referred by Cushman from the shallow water of the Atlantic coast (1944, p. 31) are not identical, but specimens from Porto Rico so labeled by him are very close to my specimens. D'Orbigny's species was described from Martinique. This question must be left open until further study of West Indian specimens can be made. Adult forms from the Portsmouth area have five chambers in the last-formed whorl, young specimens about six.

DISCORBIS SQUAMATA n.sp.

(Plate 6, figures 10a, b, 11)

Test small, flat, slightly convex on the dorsal side, concave on the ventral, usually with a small ventral plug, composed of 2 to 2½ whorls; periphery subacute, non-lobulate; chambers 5 to 6 in the adult whorl, slightly curved, increasing gradually in size as added, on the ventral side often with lip-like processes extending into the umbilical area; sutures narrow, flush with the surface, slightly curved on the dorsal side, on the ventral side depressed, flexuose; wall thin, often translucent, finely perforate on both sides; aperture normal. Maximum diameter 0.14–0.25 mm.; minimum diameter 0.11–0.21 mm.

Holotype from station 356 at a depth of 29 m., N. Lat. 42°49.8′, W. Long. 70°45.0′.

This species occurs at a few stations shallower than 50 m. It is smaller and more compressed than *D. subaraucana* Cushman, has fewer chambers to the whorl and a more finely perforate test. Unlike *D. columbiensis* in the same general area, it shows little variation. Somewhat larger specimens closely resembling this species but having seven to eight chambers have been observed from Block Island Sound south of Cape Cod. It is probable that the conception of the species should be expanded to include these forms.

EPONIDES FRIGIDUS (Cushman)

(Plate 6, figures 12a, b)

Pulvinulina karsteni H. B. Brady (not Reuss), 1864, Trans. Linn. Soc. London, vol. 24, p. 470, pl. 48, fig. 15; 1878, Ann. Mag. Nat. Hist., ser. 5, vol. 1, p. 436, pl. 21, fig. 11.

Pulvinulina repanda (Fichtel and Moll), var. *karsteni* Parker and Jones, 1865, Phil. Trans. Roy. Soc. London, vol. 155, p. 396, pl. 14, figs. 14, 15, 17.

Pulvinulina frigida Cushman, 1921 (1922), Contr. Canadian Biol., p. 144.

The Portsmouth specimens are much smaller than those of the Arctic region. They reach a maximum diameter of 0.32 mm. Although Cushman states the maximum diameter to be 0.4 mm., specimens up to 0.6 mm. have been observed from the Arctic. Otherwise, the species in the Portsmouth area appears to be typical. It is interesting that all the specimens obtained by Cushman (1944, p. 34) from the shallow waters of this area belong to the variety *calidus*. I examined these specimens at the Cushman Laboratory and found them to be very typical and quite different from the deeper-water form with its acute periphery.

This species is reported as *E. frigidus* var. *calidus* by Parker (1948, p. 238) from all facies south of Cape Cod.

EPONIDES UMBONATUS (Reuss)

(Plate 6, figures 13a, b)

Rotalina umbonata Reuss, 1851, Zeitschr. deutsch. geol. Ges., vol. 3, p. 75, pl. 5, figs. 35a-c.

Truncatulina tenera H. B. Brady, 1884, Rept. Voy. CHALLENGER, Zoöl., vol. 9, p. 665, pl. 95, figs. 11a-c.

This species is rare. It is not reported from the Arctic but is found south of Cape Cod at stations deeper than 90 m. (Parker, 1948, p. 225).

EPONIDES WRIGHTII (H. B. Brady)

(Plate 6, figures 14, 15)

Discorbina parisiensis J. Wright (part) (not d'Orbigny), 1876–77 (1877), Proc. Belfast Nat. Field Club., App. p. 105, pl. 4, figs. 2a-c.

Discorbina wrightii H. B. Brady, 1881, Ann. Mag. Nat. Hist., ser. 5, vol. 8, p. 413, pl. 21, figs. 6a-c.

This species is very rare in this area. It is more abundant in shallow water samples of the Long Island Sound area.

PATELLINA CORRUGATA Williamson

(Plate 6, figures 16, 17)

Patellina corrugata Williamson, 1858, Rec. Foram. Great Britain, p. 46, pl. 3, figs. 86–89.

This species is rare. It occurs in the Arctic and in the Long Island Sound - Buzzards Bay area.

PNINAELLA (?) PULCHELLA n.sp.

(Plate 6, figures 18a, b, 19, 20)

Test small, compressed, very slightly convex on the dorsal side, slightly concave on the ventral side, with secondary plates forming over the apertures extending ½–⅔ of the way to the periphery forming a star-shaped central portion; periphery narrow, rounded; chambers 7–9 in the last-formed whorl, narrow, increasing very gradually in size as added, uninflated, the secondary plates somewhat inflated, each one successively covering the aperture of the previous chamber; sutures on the dorsal side flush with the surface, slightly curved, slightly limbate, on the ventral side somewhat depressed; wall thin, finely perforate, often translucent; aperture loop-shaped, variable in size, extending up into the chamber on the ventral side, occasionally absent when a secondary chamber has formed after the last-formed chamber. Maximum diameter 0.22 mm.; maximum thickness 0.07 mm.

Holotype from station 356 at a depth of 29 m., Lat. 42°49.8′N., Long. 70°45.0′W.

This species is questionably placed in the genus *Pninaella* because of its close resemblance to *Pninaella nitidula* (Chaster) which was placed in this genus by Brotzen (1948, p. 120). There can be no question of the generic similarity of the two species. I have had considerable difficulty, however, in discovering from Brotzen's description the relationship between *P. nitidula* and his generic description and genotype *P. scanica* Brotzen. He makes no mention of the secondary plates formed over the apertures, which would seem to be an important generic character. They are apparently not present in the genotype. Specimens of *P. nitidula*, however, sent by Heron-Allen to Cushman show the secondary plates. The problem cannot be solved until Brotzen's types of *P. scanica* can be studied and compared with those of the Recent species.

P. (?) *pulchella* differs from *P. nitidula* in having a rounded, non-keeled periphery, in the secondary plates which do not extend to the periphery, and in having a maximum of 9 instead of 8 chambers in the last-formed whorl. Although our specimens of *P.* (?) *pulchella* are larger than the described specimens of *P. nitidula*, larger specimens of that species have been observed from the Mediterranean. Some of the Mediterranean specimens have 2½ whorls.

P. (?) *pulchella* is found only at a few stations at less than 50 m. It also occurs near Fishers Island, at the entrance to Long Island Sound. In both places it is associated with *Discorbis squamata* n.sp.; although the two species show some similarities there seems to be no doubt of their independent identities.

Family CASSIDULINIDAE

CASSIDULINA ALGIDA Cushman

(Plate 6, figures 21a, b)

Cassidulina algida Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 35, pl. 4, fig. 24.

This species is easily identified by its inflated chambers. This feature is not emphasized by Cushman but study of the types and the abundant specimens from the Portsmouth area shows it to be one of the most outstanding characteristics. I have also observed the species in material from Baffin Bay, Greenland. It is not reported elsewhere.

CASSIDULINA ISLANDICA Nφrvang var. MINUTA Nφrvang

(Plate 6, figures 22a, b, 23)

Cassidulina islandica Nørvang var. *minuta* Nørvang, 1945, Zoöl. Iceland, vol. 2, pt. 2, Foraminifera, p. 43, text figs. 8a-c.

This variety apparently is identical with Nφrvang's. It has the triangular tooth described by him. Although the chambers are somewhat inflated, the inflation is much less than in *C. algida*. The specimens correspond in size with Nφrvang's figured specimens (0.24–0.26 mm. in length). Somewhat larger specimens have been observed from Dundas Harbor and North Devon Harbor, off Greenland (up to 0.32 mm. in length).

CASSIDULINA NORCROSSI Cushman

(Plate 6, figures 24, 25)

Cassidulina norcrossi Cushman, 1933, Smithsonian Misc. Coll., vol. 89, no. 9, p. 7, pl. 2, figs. 7a-c.

This species is reported from the Arctic and the Gulf of Maine by Cushman (1944, p. 35). South of Cape Cod it occurs in zones 3 and 4, 90 m. to 680 m., but reaches its peak of frequency beyond 300 m. (Parker, 1948, p. 225). It is not common in the Portsmouth area.

Family ANOMALINIDAE

CIBICIDES LOBATULUS (Walker and Jacob)

Nautilus lobatulus Walker and Jacob, 1798, Adams Essays, Kannmacher's ed., p. 642, pl. 14, fig. 36.

This species is very abundant in this area. It is found at all latitudes in the north Atlantic.

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Contribution No. 589, Woods Hole Oceanographic Institution
Contribution No. 7, Marine Foraminifera Laboratory.

PLATE 1

Fig. 1. *Crithionina pisum* Goës var. *hispida* Flint. X 48. Sta. 507.

Fig. 2. *Proteonina atlantica* Cushman. X 48. Sta. 668.

Fig. 3. *Proteonina difflugiformis* (H. B. Brady). X 38. Sta. 8.

Fig. 4. *Urnulina compressa* Cushman. X 70. Sta. 404.

Fig. 5. *Hippocrepina indivisa* (Parker). X 48. Sta. 163.

Figs. 6, 7. *Reophax arctica* H. B. Brady. X 70. (6) Sta. 649; (7) Sta. 82.

Figs. 8, 9. *Hormosina* sp. X 70. Sta. 21.

Fig. 10. *Hyperammina elongata* H. B. Brady. X 48. Sta. 21.

Figs. 11–19. *Reophax curtus* Cushman and variants. (11–18) X 48. (11, 12) Sta. 668; (13) Sta. 384; (14, 15) Sta. 667; (16) Sta. 521; (17) Sta. 53; (18) Sta. 482; (19) X 38. Sta. 14.

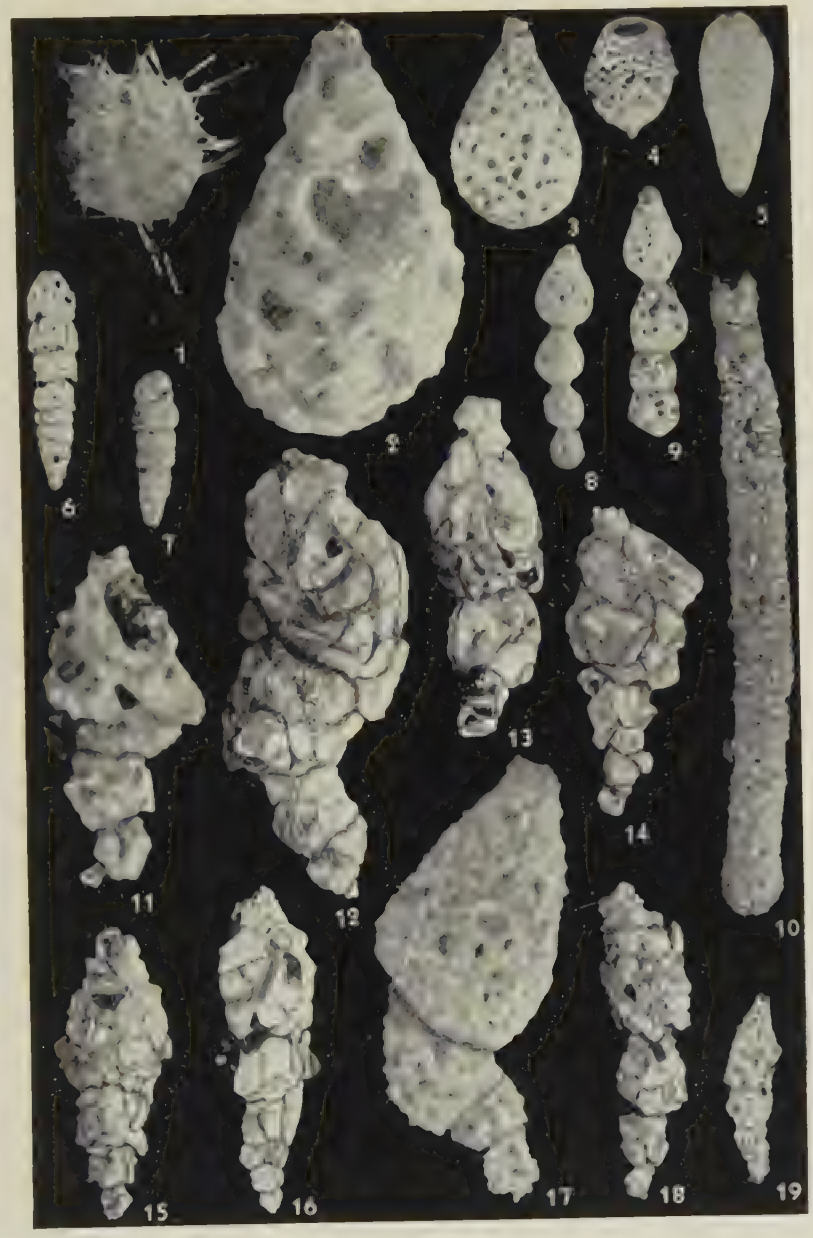
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PLATE 2

Fig. 1. *Reophax gracilis* Kiaer. X 70. Sta. 74.

Fig. 2. *Reophax scottii* Chaster. X 70. Core 130, no. 1.

Figs. 3, 4. *Ammodiscus catinus* Höglund. (3) X 70; (4) X 47. Sta. 275.

Fig. 5. *Ammodiscus minutissimus* Cushman. X 48. Sta. 275.

Fig. 6. *Glomospira gordialis* (Jones and Parker). X 48. Sta. 668.

Figs. 7, 12. *Labrospira arctica* n.sp. X 70. (7) Paratype; (12) Holotype. Baffin Bay, Sta. 12.

Figs. 8, 9, 10. *Ammobaculites cassis* (Parker). (8) X 48. Core 47, no. 1; (9, 10) X 34. (9) Sta. 144; (10) Sta. 618.

Fig. 11. *Haplophragmoides bradyi* (Robertson). X 70. Sta. 275.

Figs. 13, 14. *Haplophragmoides glomeratus* (H. B. Brady). X 48. (13) Sta. 668; (14) Sta. 647.

Figs. 15, 17, 18, 19, 20. *Labrospira jeffreysii* (Williamson). X 48. (15, 18) Sta. 275; (17) Sta. 40; (19) Sta. 647; (20) Sta. 27.

Figs. 16a, b. *Labrospira crassimargo* (Norman). X 48. Sta. 668.

Figs. 21, 22. *Labrospira* cf. *nitida* (Goës). X 48. Sta. 21.

Figs. 23, 24. *Recurvoides turbinatus* (H. B. Brady). X 48. Sta. 668.

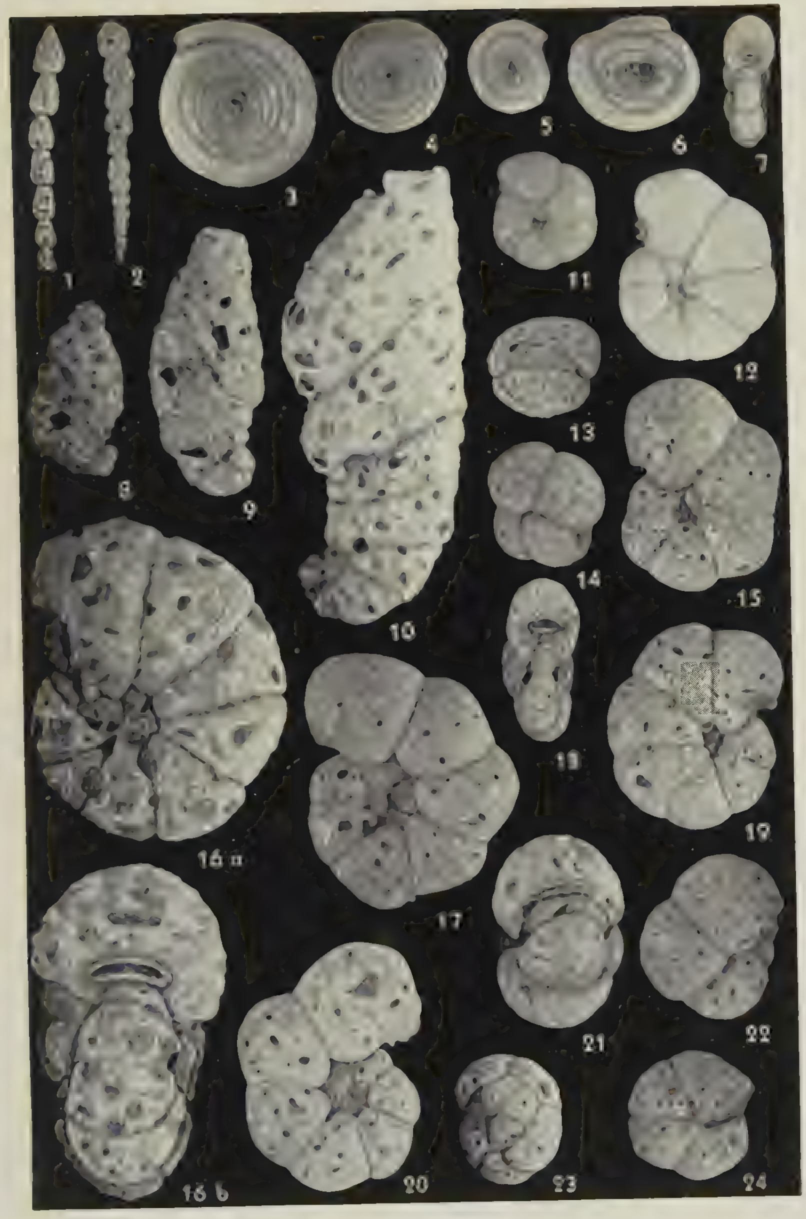
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PLATE 3

Figs. 1, 2. *Spiroplectammina biformis* (Parker and Jones). X 70. Sta. 48.

Figs. 3, 4, 5, 6, 7, 8. *Spiroplectammina typica* Lacroix. (3, 4, 5, 7) X 48; (6, 8) X 70. (3, 6) Sta. 706; (4) Sta. 642; (5) Sta. 685; (7, 8) Sta. 625.

Figs. 9, 10, 11. *Textularia torquata* n.sp. X70. (9) Holotype; (11) Paratype. Sta. 114; (10) Sta. 35.

Figs. 12, 13. *Eggerella advena* (Cushman). (12) X 70. Sta. 668; (13) X 48. Sta. 317.

Figs. 14, 18. *Valvulina conica* Parker and Jones. (14) X 48. (18) X 38. Sta. 718.

Figs. 15, 16. *Miliammina fusca* (H. B. Brady). (15) X 48. (16) X 70. Sta. 404.

Fig. 17. *Pyrgo subsphaerica* (d'Orbigny). X 48. Sta. 57 (bottom).

Figs. 19a, b. *Quinqueloculina arctica* Cushman. X 36. Sta. 610.

Figs. 20a, b. *Quinqueloculina frigida* n.sp. X 48. Holotype. Sta. 610.

Figs. 21a, b, 22a, b. *Quinqueloculina seminula* (Linné). X 48. (21) Sta. 356. (22) Sta. 439.

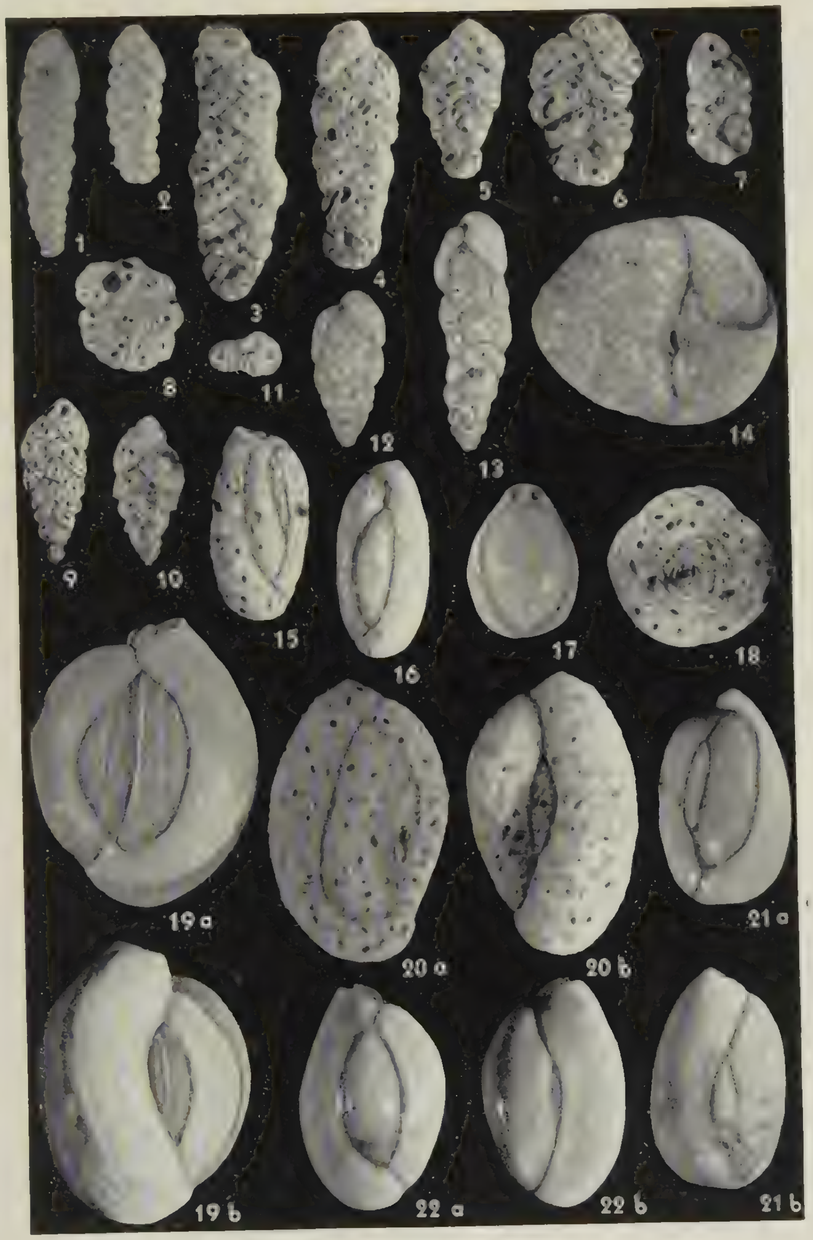
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PLATE 4

Figs. 1, 2. *Quinqueloculina seminula* (Linné). X 36. (1) Sta. 439; (2) Sta. 395.

Figs. 3a, b. *Trochammina advena* Cushman. X 48. Sta. 526.

Figs. 4a, b. *Quinqueloculina subrotunda* (Montagu). X 48. Sta. 610.

Fig. 5. *Triloculina tricarinata* d'Orbigny. X 48. Sta. 708.

Figs. 6, 10. *Trochammina inflata* (Montagu). (6) X 70. (10) X 48. Sta. 404.

Figs. 7a, b. *Trochammina lobata* Cushman. X 48. Sta. 338.

Figs. 8a, b. *Trochammina macrescens* H. B. Brady. X 48. Sta. 404.

Figs. 9a, b. *Trochammina quadriloba* Höglund. X 70. Sta. 85.

Figs. 11, 12. *Trochammina squamata* Parker and Jones. X 70. Sta. 610.

Figs. 13, 14. *Trochammina ochracea* (Williamson). X 70. Sta. 610.

Figs. 15, 16. *Trochammina* (*Remaneica*) *helgolandica* Rhumbler. X 70. Sta. 610.

Figs. 17, 18, 19. *Trochamminella atlantica* n.sp. X 70. (17) Holotype; (18, 19) Paratypes. Core 16, Melville Sound.

Figs. 20, 21. *Oolina costata* (Williamson). X 48. Sta. 708.

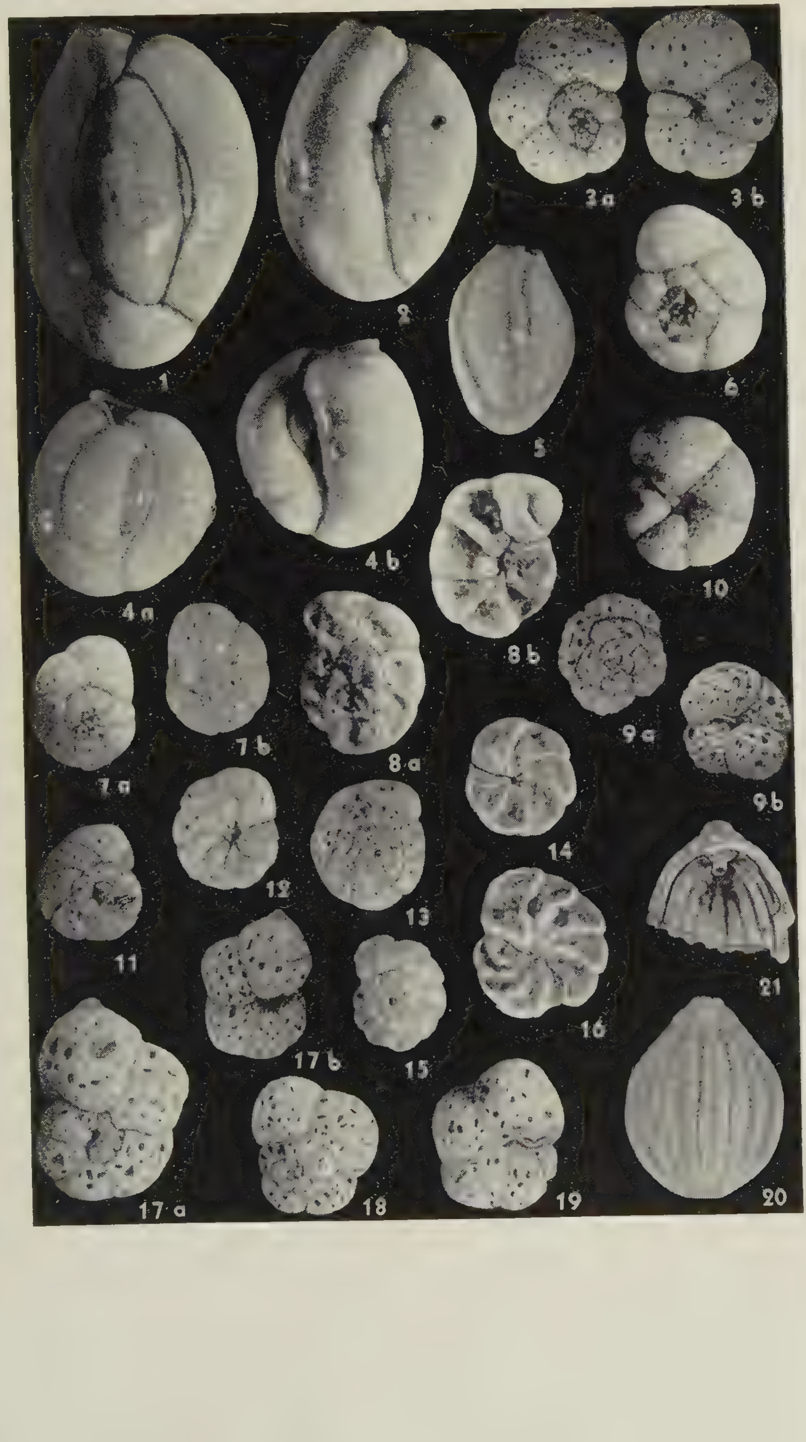
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PLATE 5

Fig. 1. *Pseudopolymorphina novangliae* (Cushman). X 36. Sta. 708.

Figs. 2, 3. *Astrononion stellatum* Cushman and Edwards. X 70. Sta. 556.

Fig. 4. *Elphidium advenum* (Cushman) var. *margaritaceum* Cushman. X 48. Sta. 404.

Figs. 5, 6, 7. *Elphidium articulatum* d'Orbigny. (5) X 36. Sta. 556; (9, 7) X 48. Sta. 610.

Fig. 8. *Elphidium excavatum* (Terquem). X 38. Sta. 610.

Fig. 9. *Elphidium subarcticum* Cushman. X 48. Sta. 610.

Figs. 10, 11. *Elphidium incertum* (Williamson) var. *clavatum* Cushman. X 48. (10) Sta. 610; (11) Sta. 708.

Fig. 12. *Nonion labradoricum* (Dawson). X 48. Core 47, no. 10.

Figs. 13a, b, 14a, b. *Nonionella auricula* Heron-Allen and Earland. X 48. (13) Sta. 610; (14) Sta. 556.

Figs. 15, 16. *Nonionella turgida* (Williamson) var. *digitata* Nørvang. X 48. Core 53 (bottom).

Fig. 17. *Bolivina pseudoplicata* Heron-Allen and Earland. X 70. Sta. 556.

Figs. 18, 19. *Angulogerina angulosa* (Williamson). (18) X 48. Sta. 248. (19) X 70. Sta. 275.

Figs. 20, 21. *Bolivina pseudopunctata* Höglund. X 70. Sta. 246.

Fig. 22. *Bolivina subaenariensis* Cushman. X 48. Core 26, no. 4.

Figs. 23, 24, 25. *Bulimina aculeata* d'Orbigny. X 48. (23) Core 26, no. 3; (24) Sta. 275; (25) Core 595, no. 5.

Fig. 26. *Bulimina marginata* d'Orbigny. X 48. Core 2, no. 13.

Figs. 27, 28. *Buliminella elegantissima* (d'Orbigny). X 70. Sta. 372.

Fig. 29. *Globobulimina* (*Desinobulimina*) *auriculata* (Bailey). X 48. Sta. 190.

Figs. 30a, b. "*Robertina*" cf. *charlottensis* (Cushman). X 48. Sta. 703.

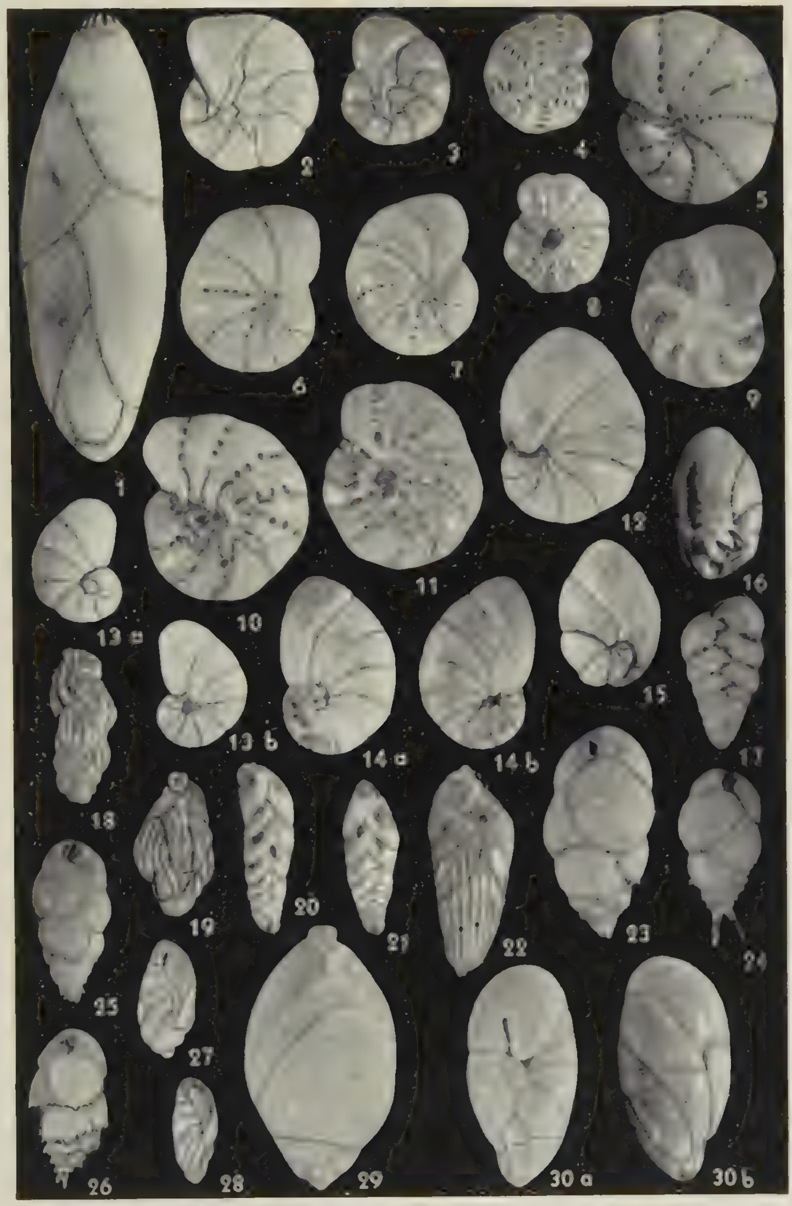
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PLATE 6

Figs. 1a, b, 2a, b. *Virgulina complanata* Egger. X 70. Core 27 (bottom).

Figs. 3, 4, 5, 6. *Virgulina fusiformis* (Williamson). X 70. Sta. 610.

Figs. 7a, b, 8a, b, 9a, b. *Discorbis columbiensis* Cushman. (7) X 48. (8, 9) X 70. (7, 8) Sta. 404; (9) Sta. 395.

Figs. 10a, b, 11. *Discorbis squamata* n.sp. X 70. (10) Holotype; (11) Paratype. Sta. 356.

Figs. 12a, b. *Eponides frigidus* (Cushman). X 70. Sta. 647.

Figs. 13a, b. *Eponides umbonatus* (Reuss). X 48. Core 2, no. 12.

Figs. 14, 15. *Eponides wrightii* (H. B. Brady). X 38. Sta. 678.

Figs. 16, 17. *Patellina corrugata* Williamson. X 70. Sta. 610.

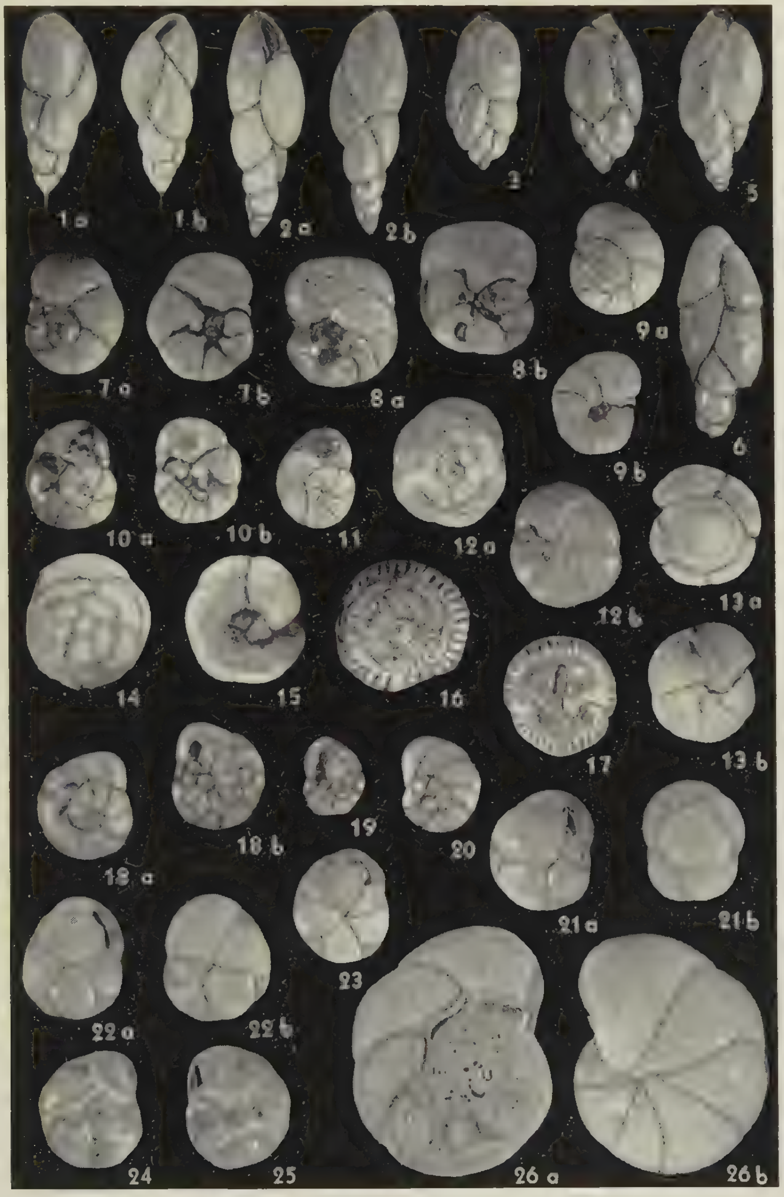
Figs. 18a, b, 19, 20. *Pninaella* (?) *pulchella* n.sp. (18, 20) X 86. (19) X 60. (18) Holotype; (19, 20) Paratypes. Sta. 356.

Figs. 21a, b. *Cassidulina algida* Cushman. X 48. Sta. 610.

Figs. 22a, b, 23. *Cassidulina islandica* Nørvang var. *minuta* Nørvang. X 70. (22) Sta. 334; (23) Core 2, no. 13.

Figs. 24, 25. *Cassidulina norcrossi* Cushman. X 48. Core 2, no. 13.

Figs. 26a, b. *Cibicides lobatulus* (Walker and Jacob). X 48. Sta. 610.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Bulletin of the Museum of Comparative Zoölogy
AT HARVARD COLLEGE
Vol. 106, No. 10

FORAMINIFERAL DISTRIBUTION IN THE LONG ISLAND SOUND — BUZZARDS BAY AREA

By Frances L. Parker

With Five Plates

CAMBRIDGE, MASS., U. S. A.
PRINTED FOR THE MUSEUM

May, 1952

No. 10.—*Foraminiferal Distribution in the Long Island Sound — Buzzards Bay Area*[1]

By Frances L. Parker

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[1] Received for publication October 8, 1951.

INTRODUCTION

The area investigated includes Long Island Sound south and east of the Housatonic River, Gardiners Bay, Block Island Sound, the approaches to Buzzards Bay and most of Buzzards Bay. The purpose of this investigation is to give the distribution of the Foraminifera and to analyze the faunal facies. Some of the physical characteristics of the environments will be described including salinity and temperature distribution and types of sediment. The types are deposited at the U. S. National Museum in Washington, D. C.

This investigation was supported by the Office of Naval Research (project number NR 081 050). Most of the samples were collected by H. C. Stetson and C. R. Hayes using the facilities of the Woods Hole Oceanographic Institution. Figures and tables were drafted by Misses J. F. Peirson and S. F. Rush. Miss Ruth Todd kindly compared specimens of *Elphidium incertum* (Williamson) with material at the National Museum.

LOCATION OF SAMPLES

The samples used in this survey were collected at various times and by different methods. Their positions are shown in figures 1 and 2. Table 1 gives geographic positions, depth, and type of sediment.

The stations may be divided into six groups as follows:

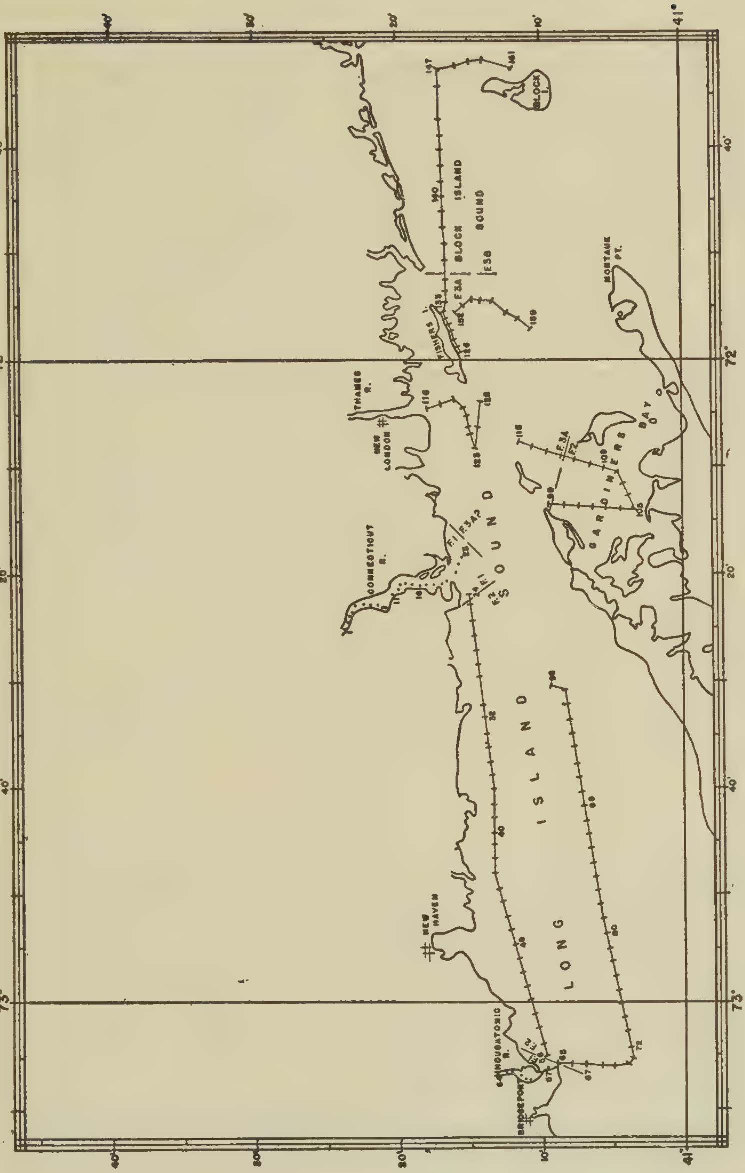
1. Long Island Sound. A series of samples was taken for about 3 miles up the Housatonic River (58–64); a second series from the mouth of the Housatonic River to the mouth of the Connecticut River (21–56); a third series south from the mouth of the Housatonic River to about the middle of the Sound at Lat. 41° 03.7′ N and then east to Long. 72° 30.4′ W (57–98); and a fourth series up the Connecticut River for about 7½ miles (1–20).

2. Gardiners Bay. Two series of samples were taken (99–115).

Groups 1 and 2 were collected in August, 1948, partly with an orange-peel dredge (Phleger, p. 320) and partly with the Phleger bottom sampler (Phleger, p. 321).

3. West of Fishers Island. This series extends south from the mouth of the Thames River (116–125). The samples were collected in the summer of 1942 with an underway bottom sampler designed by Ewing et al (1946, p. 925).

4. Block Island Sound. One series extends south from the east end of Fishers Island for about 5 miles (152–159); a second series extends along the southern shore of Fishers Island east to Long. 71° 32.6′ W and then south to a point just east of the mid-point of Block Island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50'

Fig. 1. Map of Long Island Sound and vicinity showing locations of stations and faunal facies boundaries

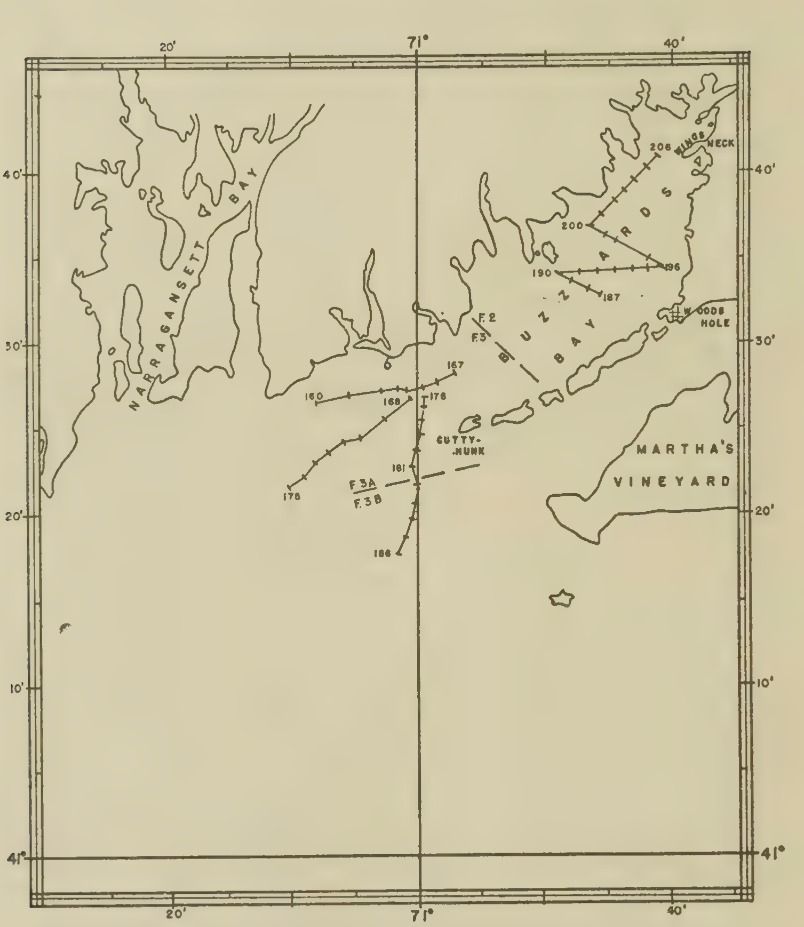
20'
71°
40'
40'
30'
20'
10'
41°
NARRAGANSETT BAY
BUZZARDS BAY
WINGS NECK
206
200
196
190
187
WOODS HOLE
F.2
F.3
167
160
168
178
176
CUTTY-HUNK
181
F.3A
F.3B
186
MARTHA'S VINEYARD

Fig. 2. Map of Buzzards Bay and vicinity showing locations of stations and faunal facies boundaries

(126–151). These samples were collected with the underway bottom sampler in the summer of 1942.

5. Approaches to Buzzards Bay. There are three series of samples converging in the mouth of the bay (160–186). They were collected in the summer of 1942 with the underway bottom sampler.

6. Buzzards Bay. The stations follow a zigzag course down the bay from a point in the center west of Wings Neck to a point about 8 miles southwest of the starting point (187–206). These samples were collected with a dwarf orange-peel bottom sampler in the summer of 1948.

METHODS OF STUDY

The samples were treated in a similar, though simplified, manner to that described in a previous paper (Parker, 1948, p. 217). They were subdivided to give an amount of material containing about 300 specimens. The samples taken with the underway bottom sampler sometimes contained less than this number without subdivision.

The Foraminifera were counted and percentages of the various species calculated and tabulated. Total population counts were calculated for those samples taken with the Phleger bottom sampler and orange-peel dredge. The samples taken with the underway bottom sampler were too variable in size to give comparative total populations. Tabulations of 150 of the 206 samples counted appear in Tables 2–6. Some species were found to have too scattered an occurrence to be of use in analysis. These have been omitted from the tables although some are listed elsewhere. Other species are too rare to appear in percentage counts and are considered to be of little immediate value in an ecologic study.

TEMPERATURE AND SALINITY DISTRIBUTION

The temperature and salinity data given below have been obtained from Sumner, Osborn and Cole (1911), Galtsoff and Loosanoff (1939), Riley (1948), and from records filed at the Woods Hole Oceanographic Institution.

Temperature

Minimum temperatures in Long Island Sound occur in February. West of the Connecticut River there is almost complete mixing of the water at this time giving a bottom temperature of about 1°C. An unusually warm winter might result in slightly higher temperatures but it is expected that this minimum would obtain during most years. In Gardiners Bay similar minimum temperatures probably occur although few data are available. Somewhat higher minimum temperatures of about 3°C. occur east of the Connecticut River. This 3°C. February bottom temperature extends eastward to the entrance of Buzzards Bay where the temperature drops to 1°C. For Buzzards Bay there are few data available for the period between November and March. From the conditions at the mouth of the bay, however, and by a comparison of the March figures for Buzzards Bay and Long Island Sound, it may be deduced that minimum bottom temperatures of 1°C. are to be expected. In such an area complete mixing and thus isothermal water would be expected during the winter months.

Maximum bottom temperatures occur during August. In western Long Island Sound a maximum of 21°C. is reached. To the eastward the temperature decreases to 18°C., the maximum observed south of the Connecticut River. It is probable that higher temperatures occur close to shore in very shallow water. The maximum bottom temperature in Gardiners Bay is probably about 21°C. In the region between Gardiners Bay and the mouth of the Thames River the maximum is 18°C. and this condition generally prevails in the western end of Block Island Sound. August bottom temperatures drop to about 15°C. toward the east in Block Island Sound, probably due to a marked surface thermocline and no deep mixing of the water. Between Block Island Sound and Cuttyhunk a maximum bottom temperature of only 13°C. is reached although the surface temperatures are slightly higher. At the entrance to Buzzards Bay the yearly maximum bottom temperature rises again to 18°C. Conditions in Buzzards Bay are similar to those of the western part of Long Island Sound with a maximum of about 18°C. near the entrance, increasing to 22°C. opposite Wings Neck.

Differences between yearly maximum and minimum temperatures in the various parts of the area are of interest. From west to east in Long Island Sound the difference varies from 20°C. to 17°C. From the Connecticut River eastward through Block Island Sound the difference decreases from 15°C. to 12°C. Between Block Island Sound and Cuttyhunk it is about 11°C., rising to 16°C. at the entrance to Buzzards Bay, and in Buzzards Bay it increases from 16°C. in the southwest to 21°C. in the northeast.

Salinity

Salinity in this area is essentially uniform during the year. The values are lowest in the spring and highest in the fall, the maximum variation probably not exceeding 2 $^0/_{00}$ (two parts per thousand). Salinity values in the western part of Long Island Sound near Bridgeport vary from 26–28 $^0/_{00}$ excluding the Housatonic River area. The salinity increases gradually eastward to a maximum in the area between Block Island and Cuttyhunk, of 32–33 $^0/_{00}$. In Buzzards Bay these values decrease again to 30–31 $^0/_{00}$ in the vicinity of Wings Neck.

At the entrance to the various rivers in Long Island Sound very complex and varying salinity patterns are found. Relatively fresh water frequently occurs at the surface and the salinity may increase as much as 4 $^0/_{00}$ with depth. In general bottom salinities close to 25 $^0/_{00}$ may be expected just outside the river mouths. Maximum bottom salinities of 28 $^0/_{00}$ at the Housatonic River and 30 $^0/_{00}$ at the Connecticut River have been observed. Surface salinities vary from 19 $^0/_{00}$ to 25 $^0/_{00}$ at the mouth of the Housatonic River and 15 $^0/_{00}$ to 26 $^0/_{00}$ at the mouth of the Connecticut River.

There are no published data on the salinities in the rivers. Dr. Gordon A. Riley of the Bingham Oceanographic Laboratory gives the following data (personal communication): "During August, 1946, I examined the salinity distribution about three miles up the Connecticut and Thames Rivers with the salinity-temperature-depth recorder. In each case the fresh water formed a sheet about five feet thick on the surface, underlain by a strong salinity gradient, with bottom salinities nearly the same as in the Sound outside. I would guess that high salinities can be found at the bottom as far up the rivers as the visible tidal effect. . . . However, there must be considerable variation with the tide, as well as seasonal change." These tidal effects extend up the rivers farther than any samples taken for this study.

BOTTOM SEDIMENTS

In Table 1 the character of the sediment at each station is given in general terms as sand, sand and mud, mud, and stony from examination of the samples, except in the case of the samples taken with the underway bottom sampler. For the interpretation of these samples, Stetson permitted the writer to examine his unpublished charts of sediment distribution in the Block Island-Cuttyhunk area.

The sediments are distributed in the expected manner with mud and sandy mud in the bays and sand on the continental shelf outside the bay areas, with local patches of mud. Sediments in Long Island Sound along the Connecticut shore are predominantly sand, or mud and sand. In the rivers sand is predominant. South of the Housatonic River there is an area of black mud. In the central part of the Sound a silty mud predominates, presumably material washed out from the rivers. Stations 93–99 in this part of the area, however, are in sand. Gardiners Bay contains sand and mud in most of the area sampled. Between Gardiners Bay and Buzzards Bay sand predominates, although there are large patches of mud scattered through the area. In Buzzards Bay there are mud and mud-sand patches.

DESCRIPTION OF FORAMINIFERAL FACIES

Figures 3 and 4 show the distribution of species in the various facies.

Facies 1

Facies 1 is developed best in the Connecticut River (sta. 1–24) and to a much lesser extent in the Housatonic River (sta. 57–64). The

——— PERSISTENT OCCURRENCE - - - SCATTERED OCCURRENCE - SINGLE OCCURRENCE	FACIES 1		FACIES 2			FACIES 3 A	FACIES 3 B
	HOUSATONIC RIVER	CONNECTICUT RIVER	LONG ISLAND SOUND	GARDINERS BAY	BUZZARDS BAY	TRANSITION ZONES	BLOCK ISLAND SOUND S.W. OF CUTTYHUNK
Ammoastuta salsa		- - -	-			-	
Ammobaculites cf. dilitatus					- - -		
A. cf. exiguus	-	- - -				-	
A. cf. foliaceus						- - -	———
Ammoscalaria fluvidis	-	- - -				-	
Bolivina pseudoplicata			- - -		- - -	———	———
B. variabilis		-	- - -	- - -	- - -	———	
Bulimina aff. aculeata						- - -	- - -
Cibicides concentricus						- - -	
C. lobatulus			- - -		-	———	- - -
Discorbis columbiensis			- - -	- - -	- - -	———	- - -
D. squamata						- - -	-
Eggerella advena		- - -	———	———	———	———	———
Elphidium advenum	-		-	- - -	———	———	-
E. advenum var. margaritaceum		-	- - -	- - -	- - -	———	- - -
E. excavatum			- - -	- - -	———	- - -	-
E. Incertum & variants	———	- - -	———	———	———	———	———
E. Incertum (heavy shell)			———	———	———	- - -	- - -
E. selseyense					- - -		
E. subarcticum	- - -		———	———	———	———	———
Eponides frigidus						- - -	———
E. frigidus var. calidus	- - -	-	———	———	———	———	- - -
E. wrightii			-	- - -	- - -	———	-
Globulina caribaea			- - -			- - -	-
Glomospira gordialis						- - -	-
Hopkinsina pacifica atlantica			- - -	- - -	- - -		
Labrospira crassimargo							———
Lagunculina vadescens		- - -					
Leptodermella variabilis	-	———					
Miliammina fusca	- - -	———	-		- - -	-	

Figure 3. Distribution of Foraminifera by faunal facies.

——— PERSISTENT OCCURRENCE - - - SCATTERED OCCURRENCE • SINGLE OCCURRENCE	FACIES 1		FACIES 2			FACIES 3	
						A	B
	HOUSATONIC RIVER	CONNECTICUT RIVER	LONG ISLAND SOUND	GARDINERS BAY	BUZZARDS BAY	TRANSITION ZONES	BLOCK ISLAND SOUND S.W. OF CUTTYHUNK
Nonion tisburyense		- - -	———	———	- - -	- - -	
Nonionella atlantica						- - -	•
Pninaella pulchella						- - -	
Poroeponides lateralis			- - -		•	———	- - -
Proteonina atlantica			- - -			———	———
P. hancocki	•	———					
P. lagenarium		———	- - -				
P. sp. A			- - -		———	•	
P. sp. B		- - -					
Pseudopolymorphina novangliae			- - -	- - -	- - -	- - -	- - -
Pyrgo striatella						———	- - -
Quinqueloculina seminula			- - -	- - -	- - -	———	- - -
Q. seminula var. jugosa			- - -	•	- - -	———	- - -
Q. subrotunda			- - -	•		———	- - -
Reophax curtus						- - -	———
R. dentaliniformis			———	———	- - -		
R. nana			- - -	———	———	- - -	
Rotalia beccarii			- - -	———	———	———	———
R. beccarii var. sobrina				———	———	- - -	
R. beccarii var. tepida			- - -	- - -	- - -	•	
Textularia cf. tenuissima		•	- - -	- - -	———	•	- - -
Triloculina brevidentata				- - -	———		
Trochammina compacta			- - -	- - -	———	- - -	- - -
T. inflata	- - -	•	•		- - -	- - -	
T. lobata		•	- - -	- - -	———	———	———
T. macrescens	•	- - -	•		•	•	
T. squamata	———	———	———	———	———	———	———
Urnulina compressa	•	———					
U. difflugaeformis		- - -					
Virgulina fusiformis					- - -	- - -	- - -

Figure 4. Distribution of Foraminifera by faunal facies.

species are exposed to great extremes of temperature. No temperature data are available but the extremes must be similar to those found in the western part of Long Island Sound: 1°C. to 21°C. Salinity also may be quite variable but values of near 25 $^{0}/_{00}$ probably obtain most of the time. During floods, and especially when floods coincide with neap tides, much lower salinities must occur.

The species confined to facies 1 are:

Ammoastuta salsa Cushman and Bronnimann
Ammobaculites cf. *exiguus* Cushman and Bronnimann
Ammoscalaria fluvialis n. sp.
Lagunculina vadescens Cushman and Bronnimann
Leptodermella variabilis n. sp.
Miliammina fusca (H. B. Brady) (some exceptions)
Proteonina hancocki Cushman and McCulloch
Proteonina lagenarium (Berthelin) (some exceptions)
Proteonina sp. B
Trochammina inflata (Montagu) (some exceptions)
Trochammina macrescens H. B. Brady (some exceptions)
Urnulina compressa Cushman
Urnulina difflugaeformis Gruber

It is of interest that this list contains species identical with, or resembling, those described by Cushman and Bronnimann (1948 a, b) from mangrove swamps in the river estuaries of the west coast of Trinidad. *Ammobaculites* cf. *exiguus* was described from a station, 0–4 m. in the Gulf of Paria, Trinidad. No further distribution data of this species have been published.

Analysis of this list of species shows that there is a possible mixing of facies. The majority of forms, as far as present evidence goes, live in water which presumably never reaches a salinity greater than 25 $^{0}/_{00}$. This is not true, however, of all the species present, such as *Miliammina fusca, Trochammina macrescens,* and *T. inflata.* These species occur in small numbers outside of facies 1, at a few scattered stations along the Connecticut shore (facies 2) south of the Thames River (facies 3), at one or two stations near Narragansett Bay (facies 3), and in the upper part of Buzzards Bay (facies 2). Most of these stations are very near the shore. Phleger and Walton (1950) found *M. fusca* and *T. inflata* in Barnstable marsh, the latter in great abundance. They were found only at a few stations outside the marsh, mostly near the outlet. The salinity of the water in Barnstable marsh is usually about 30 $^{0}/_{00}$, except after heavy rains. It seems probable that specimens of these species found in the present area have been derived from neighboring marshes and have been washed into the bays and possibly into the rivers as well. They appear to be able to survive a greater range of salinity than the other species indigenous to the rivers.

Although there are no samples taken from the Thames River, several species from facies 1 are found mixed with the facies 3 fauna outside its mouth. They are *Ammoastuta salsa, Ammobaculites* cf. *exiguus,* and *Ammoscalaria fluvialis.*

In the Connecticut River there are no Foraminifera at sta. 1–5 except for a single occurrence of *Proteonina lagenarium.* The facies is well developed at most of the remaining stations. Starting at sta. 13 the occurrence of *Eggerella advena* gives evidence of mixing with facies 3. *Elphidium incertum* has its first occurrence at sta. 15.

It is difficult to explain the poor development of facies 1 in the Housatonic River. It is possible that there is less outflow of water and more tidal effect in the area sampled which cause the water to be similar to that of the bay outside the mouth. There is a greater abundance of the species indigenous to Long Island Sound in this area than in the Connecticut River.

As at the mouth of the Thames River, there is some mixing of the facies 1 species with facies 2 near the mouths of the Connecticut and Housatonic Rivers.

Facies 2

Facies 2 is found in Long Island Sound as far east as the Connecticut River (sta. 25–56, 65–98), in Gardiners Bay (sta. 100–111) and in Buzzards Bay (sta. 187–206). There is some evidence of a gradual change from facies 2 to facies 3 in the central part of Long Island Sound, as indicated below in the discussion of facies 3. A transitional zone between facies 1 and 2 is found at the mouth of the Connecticut River from sta. 20–24.

The fauna in facies 2 is exposed to temperatures varying from 1°C. to 21°C., and at the outer limits the minimum temperature increases to 2°C. Salinities of 28–30 $^0/_{00}$ probably prevail with a seasonal variation of about 2 $^0/_{00}$. No data are available for Gardiners Bay but salinities taken at the bay entrance probably are indicative.

The species confined to facies 2 are:

Ammobaculites cf. *dilitatus* Cushman and Bronnimann (Buzzards Bay only)
Elphidium selseyensis (Heron-Allen and Earland) (Buzzards Bay only)
Hopkinsina pacifica atlantica Cushman
Nonion tisburyensis Butcher (some exceptions)
Proteonina sp. A

Reophax dentaliniformis H. B. Brady
Reophax nana Rhumbler
Rotalia beccarii (Linné) var. *tepida* Cushman (some exceptions)
Rotalia beccarii (Linné) var. *sobrina* Shupack (some exceptions)
Textularia cf. *tenuissima* Earland (some exceptions) [see footnote p. 458]
Triloculina brevidentata Cushman

In addition to the above species there are some that show a much greater abundance in this facies than elsewhere. A heavy-shelled variant of *Elphidium incertum* (Williamson) (pl. 4, figs. 1, 2) forms a large percentage of the fauna. This variant is also found in small numbers at a few scattered stations in facies 3 and occasionally in greater abundance, but in facies 2 it is very abundant except in the central area of Long Island Sound. *Trochammina compacta* n. sp. reaches its greatest abundance in facies 2 in Buzzards Bay.

The distribution of *Nonion tisburyensis* is of interest. It is found with some overlap into facies 1 at the mouth of the Connecticut River, but is best developed along the Connecticut shore and in Gardiners Bay. The occurrence in Buzzards Bay is scattered and it is almost absent from the central portion of Long Island Sound. It appears to be a transition species between facies 1 and 2.

The following species are the most abundant constituents of facies 2:

Eggerella advena (Cushman)
Elphidium incertum and/or variants
Elphidium subarcticum Cushman
Eponides frigidus (Cushman) var. *calidus* (Cushman and Cole)

Aside from the distribution of attached forms, discussed later, there is little indication of distribution controlled by sediments. The heavy-shelled variant of *Elphidium incertum* is frequently more abundant in mud than sand but not consistently so.

Facies 3

In the following discussion, facies 3 is divided, for convenience, into two parts: 3A being the transitional part of the facies and 3B its more complete development.

Facies 3A is found in the area between the Connecticut River and Gardiners Bay, extending eastward to 3 or 4 miles east of Fishers Island (sta. 99, 112–135, 152–159). It also occurs north and west of Cuttyhunk (sta. 160–181). Facies 3B is developed in Block Island Sound (sta. 136–151) and southwest of Cuttyhunk (sta. 182–186).

Facies 3A is transitional for the following reasons: (1) the species typical of facies 3 do not reach their full abundance, (2) one species typical of facies 3 is not found, (3) the "attached-form facies" reaches its greatest development, although it is present at occasional stations in facies 2 and facies 3B.

The temperature range in facies 3 is much less than that found in facies 1 and 2. The minimum temperature increases from 1°C. to 3°C., the latter obtaining in the facies 3B area. Similarly the maximum temperature decreases from 18°C. south of the Connecticut River to 13°C. in the area between Block Island and Cuttyhunk. It may be said, then, that for the best development of the facies in this area the temperature range is 3°C. to 15°C. The salinity between Block Island and Cuttyhunk ranges from 32–33 $^0/_{00}$. It is somewhat lower to the west but probably does not go lower than 30 $^0/_{00}$.

Species confined to facies 3 are:

Ammobaculites cf. *foliaceus* H. B. Brady (highest in 3B)
Bulimina aff. *aculeata* d'Orbigny
Cibicides concentricus (Cushman) (3A only)
Discorbis squamata Parker
Eponides frigidus (Cushman)
Globulina caribaea d'Orbigny (some exceptions)
Glomospira gordialis (Jones and Parker)
Labrospira crassimargo (Norman) (3B only)
Nonionella atlantica Cushman
Pninaella (?) *pulchella* Parker (3A only)
Proteonina atlantica Cushman (highest in 3B)
Pyrgo striatella (Cushman)
Reophax curtus Cushman (highest in 3B)
Virgulina fusiformis (Williamson) (some exceptions)

It is probable that *Discorbis squamata* and *Pninaella* (?) *pulchella* should not be considered as typical representatives of facies 3. Little is known as yet of their distribution in other areas and their occurrence in facies 3 is slight and inconclusive.

Two additional species: *Planulina mera* Cushman and *Quinqueloculina arctica* Cushman occur rarely in facies 3, but are not listed in the tables.

It is interesting to contrast facies 3 with the second depth facies, 15–90 m., found on the continental shelf south of Cape Cod (Parker, 1948). This continental shelf facies is identical in its main constituents with facies 3 in the Long Island Sound-Buzzards Bay area, which is to be expected. Certain forms found only in that facies on the continental shelf are found throughout the present area except in facies 1. These forms include: *Quinqueloculina seminula* (Linné), *Q. seminula* var. *jugosa* Cushman, *Eggerella advena* (Cushman), and *Trochammina lobata* Cushman. Other species of continental shelf facies 2 found in the present facies 3 only include: *Cibicides concentricus, Globulina caribaea, Nonionella atlantica, Labrospira crassimargo,* and *Pyrgo striatella.* Some of the species found in facies 3 only occur in all facies of the continental shelf and slope to a depth of at least 600 m. These include: *Eponides frigidus, Proteonina atlantica, Reophax curtus,* and *Virgulina fusiformis.* It is of interest that the temperature limits of continental shelf facies 2 are 3°C. to 16°C. which are almost identical with those encountered in facies 3. The salinity varies from 31 $^0/_{00}$ to 34.6 $^0/_{00}$, which is somewhat higher than that found in facies 3.

Facies 3A contains the best development of attached forms. The species concerned are:

Cibicides lobatulus (Walker and Jacob)
Discorbis columbiensis Cushman
Poroeponides lateralis (Terquem)
Quinqueloculina subrotunda (Montagu)

It is possible that *Eponides wrightii* (H. B. Brady) should be included with this group as well as other species of Miliolidae.

These species are found on sandy or stony bottoms, which most commonly occur in the facies 3A area. The specimens are frequently attached to algae which grow best in such areas (Davis, 1911 (1913), p. 481). The attached fauna is best developed south of the Thames River and along the southern shore of Fishers Island (sta. 114, 115, 120–134). It also occurs abundantly at sta. 151 in facies 3B close to the shore of Block Island and at sta. 162 northwest of Cuttyhunk. The depths at these stations vary from 7–76 m. Cushman (1944, pp. 15, 34, 36) points out that the attached forms found in great abundance on beaches in this general area have been washed on shore attached to algae. There is a possibility that specimens have been washed into the present locations on algae as well. It seems more probable, however, considering that 75 per cent of the stations occur at a depth of 14 m. or more, that the species are living where they are found. These species form 70 per cent of the fauna at sta. 114 and at two-thirds of the stations listed above form 35 per cent or more of the fauna.

Aside from the great abundance of the attached forms in discrete areas the most abundant constituents of facies 3 are:

Eggerella advena
Elphidium subarcticum
Rotalia beccarii (3A mostly)

Eponides frigidus (3B mostly)
Eponides frigidus var. *calidus* (3A mostly)
Proteonina atlantica (sta. 135–181)

These species, except *R. beccarii* and *E. frigidus* var. *calidus,* occur on the continental shelf and adjacent slope south of Cape Cod although *E. advena* is confined to depths of less than 90 m.

Although the central part of Long Island Sound has been placed in facies 2, there is evidence that the transition to facies 3 begins in this area. A few specimens of *Proteonina atlantica* and *Globulina caribaea* occur here. In addition the heavy-shelled variant of *Elphidium incertum,* usually a most important constituent of facies 2, is not present in great abundance. In other respects, however, the area is more typical of facies 2.

DISCUSSION OF SPECIES

Fifty-seven benthonic species are included in the analysis of the area and each of these is discussed below. Only a few juvenile planktonic forms were found. The following benthonic species are omitted from the discussions as they occur only at scattered stations at very low percentages:

Armorella sphaerica Heron-Allen and Earland (facies 2)
Bolivina cf. *striatula* Cushman (facies 2, 3)
Buliminella elegantissima (d'Orbigny) (facies 2, 3)
Cornuspira planorbis Schultze (facies 2, 3)
Elphidium cf. *discoidale* (d'Orbigny) (facies 2, 3)
Patellina corrugata Williamson (facies 2, 3)
Planulina mera Cushman (facies 3 — one exception)
Quinqueloculina angulata (Williamson) (facies 2, 3)
Quinqueloculina arctica Cushman (facies 3)
Quinqueloculina lata (Terquem) (facies 2, 3)
Reophax scottii Chaster (facies 2, 3)

An intensive description of the relationship of this fauna to those north and south of the area is of little value because of insufficient data. Little work has been done on bay faunas to the south although there are considerable data on such faunas north of Cape Cod. The following notes are of some interest.

The following 6 species have not been reported elsewhere:

Ammoscalaria fluvialis n. sp.
Trochammina compacta n. sp.
Hopkinsina pacifica atlantica Cushman.

Leptodermella variabilis n. sp.
Proteonina sp. A
Proteonina sp. B

Five species are reported in the western Atlantic for the first time:

Elphidium selseyensis (Heron-Allen and Earland)
Proteonina lagenarium (Berthelin)
Reophax nana Rhumbler
Textularia cf. *tenuissima* Earland [see footnote p. 458]
Urnulina difflugaeformis Gruber

The Pacific species *Proteonina hancocki* Cushman and McCulloch has not been previously reported in the Atlantic.

Four species resembling those reported by Cushman and Bronnimann (1948a, b) from Trinidad are reported for the first time in this area:

Ammoastuta salsa
Ammobaculites cf. *dilitatus*
Ammobaculites cf. *exiguus*
Lagunculina vadescens

This is the first report of the following 7 species from south of Cape Cod:

Discorbis squamata Parker
Elphidium excavatum (Terquem)
Miliammina fusca (H. B. Brady)
Pninaella (?) *pulchella* Parker
Quinqueloculina arctica Cushman (rare)
Trochammina macrescens H. B. Brady
Urnulina compressa Cushman

Seven additional species have not been reported north of Cape Cod:

Cibicides concentricus (Cushman)
Elphidium advenum (Cushman)
Globulina caribaea d'Orbigny
Nonion tisburyensis Butcher
Nonionella atlantica Cushman
Poroeponides lateralis (Terquem)
Quinqueloculina seminula (Linné) var. *jugosa* Cushman

Cape Cod apparently forms an effective barrier for about one-third of the species, although this number may be reduced by future investigation.

The notes on individual species stress distribution although some taxonomic notes are included. More detailed information about the taxonomy of many of the species can be found in Parker's (1952, p. 393) paper on the taxonomy of the Foraminifera off Portsmouth, New Hampshire.

AMMOASTUTA SALSA Cushman and Bronnimann

(Plate 2, figures 1, 2)

Ammoastuta salsa Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 1, p. 17, pl. 3, figs. 14–16.

This species is confined to facies 1. It occurs in the Connecticut River samples and in a few samples along the Connecticut shore where the occasional specimens have probably been carried out from the river. It is also found at sta. 116 near the mouth of the Thames River. It appears to be confined to brackish water and is so reported from various localities.

AMMOBACULITES cf. DILITATUS Cushman and Bronnimann

(Plate 1, figure 23)

Ammobaculites dilitatus Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 2, p. 39, pl. 7, figs. 10, 11.

This form occurs only in facies 2 in Buzzards Bay. It is a very loosely cemented species, which may account for its rarity in washed samples. Unbroken specimens are seldom found.

AMMOBACULITES cf. EXIGUUS Cushman and Bronnimann

(Plate 1, figures 16, 17)

Ammobaculites exiguus Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 2, p. 38, pl. 7, figs. 7, 8.

This species is too rare to be identified with certainty. It is found in the Connecticut and Housatonic Rivers and at one station at the mouth of the Thames River. It appears to be larger than the Cushman and Bronnimann species but is otherwise similar. Both this species and *A.* cf. *dilitatus* are only reported from shallow water in the Gulf of Paria, Trinidad.

Ammobaculites cf. foliaceus (H. B. Brady)

(Plate 1, figures 20, 21)

Haplophragmium foliaceum H. B. Brady, 1881, Jour. Micr. Sci., vol. 21, p. 50; 1884, Rept. Voy. CHALLENGER, Zool. vol. 9, p. 304, pl. 33, figs. 20–25.

This form is confined to facies 3 where it forms as much as 7 per cent of the fauna.

Ammoscalaria fluvialis n.sp.

(Plate 1, figures 24, 25)

Test small, compressed, with about 6 chambers in the final whorl in the planispiral portion which composes most of the test in the microspheric form, uncoiled portion with 4 or 5 chambers in the megalospheric form; chambers increasing gradually in size as added; segmentation very indistinct; wall somewhat rough, composed of small sand grains which are well cemented together; aperture oval, at the end of a very short neck or constricted portion at the apex of the test. Length up to 0.5 mm.; width up to 0.3 mm.; thickness up to 0.11 mm.

Holotype from sta. 59 in the Housatonic River at a depth of 3 m., Lat. 41° 10.9′ N, Long. 73° 07.3′ W.

This species resembles *Ammobaculites salsus* Cushman and Bronnimann but differs in having a more pronounced uniserial portion, less inflated chambers, and less distinct segmentation. It has fewer chambers than *Ammoscalaria runiana* (Heron-Allen and Earland), is more compressed, with a less broadly rounded periphery. The thin, chitinous septae dividing the chambers can be plainly seen when specimens are immersed in oil of aniseed, a technique recommended by Höglund (1947, p. 18).

A. fluvialis is confined to facies 1, occurring in both the Connecticut and Housatonic Rivers and forming as much as 18 per cent of the fauna at sta. 59 in the latter. There is a single occurrence at the mouth of the Thames River.

Bolivina pseudoplicata Heron-Allen and Earland

(Plate 4, figure 11)

Bolivina pseudoplicata Heron-Allen and Earland, 1930, Jour. Roy. Micr. Soc., vol. 50, p. 81, pl. 3, figs. 36–40.

B. pseudoplicata occurs at scattered localities in facies 2 but is more common in facies 3 where it reaches a maximum of 6 per cent of the fauna. It is confined to depths between 15 m. and 90 m. on the adjacent continental shelf (Parker, 1948, p. 221).

BOLIVINA VARIABILIS (Williamson)

(Plate 4, figure 12)

Textularia variabilis Williamson, 1858, Rec. Foram. Great Britain, p. 76, pl. 6, figs. 162, 163.

This species is found in facies 2 and 3 but is more persistent in the transition zone of facies 3 (3A). It is mostly confined to sand or sand and mud.

BULIMINA aff. ACULEATA d'Orbigny

(Plate 4, figures 7, 13)

Bulimina aculeata d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 269, No. 7.

This species resembles *B. patagonica* d'Orbigny var. *glabra* Cushman and Wickenden in the shape of the chambers which are less globular and more elongate than in typical *B. aculeata*. It differs in the presence of occasional spines at the base of the chambers. It is a small form not exceeding 0.4 mm. in length and is found in small quantities in facies 3. A few specimens of typical *B. aculeata* and the related species *B. marginata* d'Orbigny also occur in this facies but are not listed in the tables.

CIBICIDES CONCENTRICUS (Cushman)

(Plate 5, figures 10a, b)

Truncatulina concentrica Cushman, 1918, U. S. Geol. Surv. Bull. 676, p. 64, pl. 21, fig. 3.

This species is confined to transition facies 3A, chiefly in the area west of Cuttyhunk, where it occurs at low frequencies. The species has an unusual distribution elsewhere along the continental shelf south of Cape Cod (Parker 1948, p. 222) occurring at depths of 36 m. or less off the New Jersey coast and 68 m. or less off Maryland. Off Block Island and Martha's Vineyard it is found only rarely, not occurring in sufficient numbers to appear in frequency counts of the samples. Its absence from this area and from facies 3B in Block Island Sound and southwest of Cuttyhunk is difficult to explain. The species is common south of Cape Hatteras and it is possible that it requires the slightly higher maximum temperatures found in facies 3A for its reproduction. This would be in agreement with the observations made by Myers (1935, p. 358) in the case of *Patellina corrugata* Williamson.

CIBICIDES LOBATULUS (Walker and Jacob)

(Plate 5, figures 11a, b)

Nautilus lobatulus Walker and Jacob, 1798, Adams Essays, Kanmachers' ed., p. 642, pl. 14, fig. 36.

This species is found in the eastern part of Long Island Sound in facies 2 and very rarely in Buzzards Bay. Its chief occurrence is in facies 3A where it has the same distribution as the other attached forms, reaching frequencies up to 9 per cent in the vicinity of Fishers Island.

DISCORBIS COLUMBIENSIS Cushman

(Plate 4, figures 17a, b, 18a, b, 19a, b, 20a, b)

Discorbis columbiensis Cushman, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, p. 43, pl. 6, figs. 13a-c.

D. columbiensis is found in facies 2 and 3. It occurs in large numbers especially at nearshore stations. It is an attached form and is, therefore, most abundant in sandy and stony areas. At sta. 115 it forms 53 per cent of the fauna but usually reaches percentages only half as great at the localities where it most commonly occurs. It is reported from this area by Cushman (1944) under several names owing, probably, to its highly variable character.

DISCORBIS SQUAMATA Parker

(Plate 5, figures 1a, b)

Discorbis squamata Parker, 1952, Bull. Mus. Comp. Zoöl., vol. 106, no. 9, p. 418, pl. 6, figs. 10a, b, 11.

A few of the specimens, of which one is figured, are larger and have one to two more chambers than those obtained at the type locality in the Portsmouth area of the Gulf of Maine. The species occurs in facies 3, chiefly in the transition zone, at very low percentages.

EGGERELLA ADVENA (Cushman)

(Plate 2, figure 3)

Verneuilina advena Cushman, 1921 (1922), Contr. Canadian Biol., no. 9, p. 141.
Verneuilina polystropha Cushman (not Reuss) 1920, Rept. Canadian Arctic Exped., vol. 9, pt. M, p. 8, pl. 1, fig. 5.

This species is widely distributed throughout the area. In facies 1 it does not occur beyond sta. 13 up the Connecticut River and is absent from the Housatonic River. It is irregular in its frequency distribution but there seems to be no definite correlation with type of sediment. In general it is more abundant in samples where mud is present but there are exceptions. The species forms as much as 76 per cent of the fauna at one station in Buzzards Bay. It is confined to depths shallower than 90 m. on the adjacent continental shelf (Parker, 1948, p. 221).

ELPHIDIUM ADVENUM (Cushman)

(Plate 3, figure 9)

Polystomella advena Cushman, 1922, Publ. 311, Carnegie Instit. Washington, p. 56, pl. 9, figs. 11, 12.

Specimens from this area are less broadly carinate than those from the Tortugas. They are also smaller, the largest having a diameter of 0.43 mm. This is apparently the northern limit of distribution of this species and it is possible that the conditions are not favorable for its typical development. It is found in facies 2 and 3A with single occurrences in the other facies. It occurs chiefly in sand or mud and sand.

ELPHIDIUM ADVENUM (Cushman) var. MARGARITACEUM Cushman

(Plate 3, figure 10)

Elphidium advenum (Cushman) var. *margaritaceum* Cushman, 1930, Bull. 104, U. S. Nat. Mus., pt. 7, p. 25, pl. 10, fig. 3.

This variety is found in facies 2 and less commonly in facies 3. With the exception of one occurrence it is not found west of sta. 90 in Long Island Sound. It is most abundant in sand and forms as much as 11 per cent of the fauna.

ELPHIDIUM EXCAVATUM (Terquem)

(Plate 3, figure 13)

Polystomella excavata Terquem, 1875, Essai. Class. Anim. Dunkerque, p. 25, pl. 2, figs. 2a-f.

E. excavatum is confined mostly to facies 2, although it occurs in transition facies 3A in the Cuttyhunk area, where some mixing of facies probably occurs.

ELPHIDIUM INCERTUM (Williamson) and variants

(Plate 3, figures 14, 16, 17; plate 4, figures 1, 2)

Polystomella umbilicatula Walker and Boys var. *incerta* Williamson, 1858, Rec. Foram. Great Britain, p. 44, pl. 3, fig. 82a.

This is a very variable species in this area. Cushman's variety *clavatum* has been included under this general heading and it is probable that most of the specimens come closer to this designation than to Williamson's species. Extreme cases of the variations can be easily differentiated but when an attempt is made to separate specimens picked at random it becomes evident that the range of variation is continuous. Taken as a group the species forms the largest percentage of the fauna at most of the stations, constituting up to 90 per cent of the fauna at some stations in facies 2. In facies 3, however, it is also very common at some stations. In facies 1 it occurs in all the Housatonic River stations but not beyond sta. 15 in the Connecticut River. There is a large, thick, heavy-shelled variant, confined chiefly to facies 2, having limbate sutures which often develop heavy retral processes. Some of the specimens have supplementary apertures on the apertural face characteristic of *Cribroelphidium* but this feature is not universal. Treatment with acid to remove the outer whorls reveals a young form apparently identical with the simpler, typical form of the *clavatum* variant. It usually occurs in sediments containing at least some mud. At sta. 65–67, composed of black mud with a presumably high organic content, it was found in very large quantities to the exclusion of almost everything else. It is interesting that this variant does not occur, except in small quantities, in the central part of Long Island Sound. The chief areas of occurrence are Gardiners Bay, Buzzards Bay, a few stations along the Connecticut shore between the Connecticut and Housatonic Rivers, and several stations south of the Housatonic River.

The variants of *E. incertum* have been included under one heading in the tables and figures. In addition the occurrence of the heavy-shelled variant is given in figure 3. *E. incertum* is reported from all depths on the adjacent continental shelf and slope to a depth of 600 m. (Parker 1948) but no specimens of the heavy-shelled variant were observed.

ELPHIDIUM SELSEYENSIS (Heron-Allen and Earland)

(Plate 4, figure 9)

Polystomella striatopunctata (Fichtel and Moll) sp., Heron-Allen and Earland, 1909, Roy. Micr. Soc. Jour., p. 695, pl. 21, figs. 2a-c.

Polystomella striatopunctata (Fichtel and Moll) var. *selseyensis* Heron-Allen and Earland, 1911, ibid, p. 448.

This species is found in facies 2 in Buzzards Bay. The only previous record accompanied by figures is from the Selsey shore sand, England. Its restriction to Buzzards Bay cannot yet be explained.

ELPHIDIUM SUBARCTICUM Cushman

(Plate 4, figures 3–6, 8)

Elphidium subarcticum Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 27, pl. 3, figs. 34, 35.

This form occurs in all facies. The specimens in facies 1, however, are stunted and occur at low frequencies. This suggests that this environment is unfavorable for their development. This species forms as much as 30 per cent of the fauna and is somewhat more abundant in sand samples than in mud although it is by no means confined to sand areas. Some change, however, can be seen in regions where there are adjacent sand and mud bottoms, although not invariably so. It occurs in all facies of the adjacent continental shelf and slope (Parker, 1948).

EPONIDES FRIGIDUS (Cushman)

(Plate 5, figures 2a, b)

Pulvinulina frigida Cushman, 1921 (1922), Contr. Canadian Biol., p. 12.

Pulvinulina repanda (Fichtel and Moll) var. *karsteni* Parker and Jones, 1865, Phil. Trans. Roy. Soc. London, vol. 155, p. 396, pl. 14, figs. 14, 15, 17.

This species occurs in facies 3, where it forms as much as 10 per cent of the fauna in the Block Island Sound area. It is less common in the Cuttyhunk region. On the adjacent continental shelf and slope it is reported as *E. frigidus* var. *calidus* in all facies (Parker, 1948, p. 238).

EPONIDES FRIGIDUS (Cushman) var. CALIDUS Cushman and Cole

(Plate 5, figures 3a, b)

Eponides frigida (Cushman) var. *calida* Cushman and Cole, 1930, Contr. Cushman Lab. Foram. Res., vol. 6, pt. 4, p. 98, pl. 13, fig. 13.

This is a widely distributed variety in the area, occurring in all facies. It reaches its highest frequency in Long Island Sound with a percentage of 40 per cent. It is largely replaced in the well-developed part of facies 3 by *E. frigidus*. It is reported only from bays in this area and north of Cape Cod.

EPONIDES WRIGHTII (H. B. Brady)

(Plate 5, figures 4a, b)

Discorbina wrightii H. B. Brady, 1881, Ann. Mag. Nat. Hist., ser. 5, vol. 8, p. 413, pl. 21, figs. 6a-c.

E. wrightii is widely distributed except in facies 1. It is most common in the transition zone of facies 3 in Long Island Sound north of Gardiners Bay and off Fishers Island, with occurrences of 10 per cent and 12 per cent respectively. It is rare in western Long Island Sound and Buzzards Bay. It appears to follow the same pattern of occurrence as the various attached forms being generally restricted to sandy or stony areas, but there is no direct evidence that it is an attached form. Specimens are frequently observed in plastogamic pairs.

GLOBULINA CARIBAEA d'Orbigny

(Plate 3, figure 6)

Globulina caribaea d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, p. 135, pl. 2, figs. 7, 8.

This species is found at low frequencies in facies 3 and in facies 2 in the central part of Long Island Sound at sta. 91–97. It is confined to depths of 15 m. to 90 m. on the adjacent continental shelf (Parker, 1948, p. 221).

GLOMOSPIRA GORDIALIS (Jones and Parker)

(Plate 1, figure 13)

Trochammina squamata Parker and Jones var. *gordialis* Jones and Parker, 1860, Quart. Jour. Geol. Soc., vol. 16, p. 304; Parker and Jones, 1865, Phil. Trans. Roy. Soc. London, vol. 155, p. 408, pl. 15, fig. 32.

This species occurs at low frequencies in facies 3.

HOPKINSINA PACIFICA ATLANTICA Cushman

(Plate 4, figures 14–16)

Hopkinsina pacifica Cushman var. *atlantica* Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 30, pl. 4, fig. 1.

It has not been possible to compare the types of Cushman's species and variety but there appears to be a close resemblance between them. Their relationship cannot be varietal owing to their wide geographic separation. Even a subspecific relationship is unlikely but further information on the distribution of the two forms may clarify this. *H. pacifica atlantica* is confined to facies 2 except at sta. 113 (facies 3). It is most abundant in Gardiners Bay and Buzzards Bay, attaining frequencies of 1 per cent. The only previous record is Cushman's from 11 m. in Vineyard Sound.

LABROSPIRA CRASSIMARGO (Norman)

(Plate 1, figure 22)

Haplophragmium crassimargo Norman, 1892, Mus. Normanianum, pt. 8, p. 17.
Haplophragmium canariense Brady, 1884, (part) (not d'Orbigny), Rept. Voy. CHALLENGER, Zool., vol. 9, p. 310, pl. 35, fig. 4 (not figs. 1–3, 5).
Haplophragmoides major Cushman, 1920, Bull. 104, U. S. Nat. Mus., pt. 2, p. 39, pl. 8, fig. 6.

This species is found in facies 3B where it forms as much as 4 per cent of the fauna. On the adjacent continental shelf it is reported as *Haplophragmoides major* at depths shallower than 90 m. off Block Island and rarely at comparable depths farther south (Parker, 1948, p. 222). The species is found in the Arctic ranging southward to the area immediately south of Cape Cod which is apparently close to its southern limit of occurrence.

LAGUNCULINA VADESCENS Cushman and Bronnimann

(Plate 1, figure 8)

Lagunculina vadescens Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 1, p. 15, pl. 3, figs. 1, 2.

L. vadescens is very rare. Single specimens are found at a few stations in the Connecticut River in facies 1. The only previously reported occurrence is Cushman and Bronnimann's from a river estuary in Trinidad.

LEPTODERMELLA VARIABILIS n.sp.

(Plate 1, figures 11a, b, 12)

Test small, round to oval in transverse section, ventral side concave and compressed about the aperture, inflated below, dorsal side variably convex, more convex toward the lower part of the test; wall thin, composed of chitin usually overlain by a layer of fine sand grains of variable thickness, chitinous forms smooth, those with sand grains slightly rough; aperture round, in the upper half of the ventral side of the test, the wall around it bent in to form a raised, collar-like projection on the inner side of the test. Maximum diameter 0.29 mm.

Holotype from sta. 24, Long Island Sound, southwest of the mouth of the Connecticut River at a depth of 6½ m., Lat. 41° 15.4′ N, Long. 72° 21.8′ W.

This is the only described species of the genus having an asymmetrical pouch-like test. In this respect it resembles the genus *Marsupulina* Rhumbler. As in *L. excentrica* Cushman and Bronnimann, the aperture is placed at the upper part of the ventral side of the test but in *L. variabilis* it is circular instead of elongate. This is the only described species having a circular aperture. The variable character of the wall of the test is an unusual feature. Some specimens are almost entirely chitinous while others have a fairly heavy arenaceous coating, with a continuous gradation between the two.

The species occurs in facies 1 in the Connecticut and Housatonic Rivers and at some stations outside the mouth of the Connecticut River. It has a maximum frequency of 30 per cent. The large number of specimens found at sta. 24 may be due to deposition from the river.

MILIAMMINA FUSCA (H. B. Brady)

(Plate 2, figures 6a, b)

Quinqueloculina fusca H. B. Brady, 1870, Ann. Mag. Nat. Hist., ser. 4, vol. 6, p. 47, pl. 11, figs. 2a-c, 3.

This species occurs chiefly in facies 1 but is rare in facies 2 in what may be a transition area between the two facies. Its distribution in facies 2 is along the Connecticut shore adjacent to the rivers, at sta. 171 near Narragansett Bay, and in the upper part of Buzzards Bay at sta. 197–206. It differs from most other species characteristic of facies 1 in its apparent ability to exist in water of higher salinity. Phleger and Walton (1950, p. 280), found it in Barnstable Harbor and at a few stations in Cape Cod Bay where there is a maximum salinity of 32 ‰. It is possible that occurrences in facies 2, all of which are at nearshore stations, are caused by outwash from marshes.

NONION TISBURYENSIS Butcher

(Plate 3, figures 7, 8)

Nonion tisburyensis Butcher, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 1, p. 22, text figs. 1–3.

This species is mostly confined to facies 2 with some overlap into facies 1. It is also found in facies 3A at the mouth of the Thames River and at one station west of Cuttyhunk. It apparently tolerates water of salinities varying from 20 $^0/_{00}$ to 30 $^0/_{00}$. This agrees with the reported occurrences of the species in Great Pond, Falmouth, and Tisbury Great Pond on Martha's Vineyard.

NONIONELLA ATLANTICA Cushman

(Plate 3, figures 15a, b)

Nonionella atlantica Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 90, pl. 20, figs. 4, 5.

Nonionella atlantica is found in small quantities in facies 3. This is apparently the species figured by Cushman (1944, p. 25, pl. 3, figs. 26, 27) as *N. auricula* Heron-Allen and Earland although that species has been observed very rarely in this area also. *N. atlantica* is reported on the continental shelf south of Cape Cod as *Nonion sloanii* (d'Orbigny) by Parker (1948, p. 222) in water shallower than 90 m. off the coast of Maryland with rare occurrences at similar depths farther north.

PNINAELLA (?) PULCHELLA Parker

(Plate 5, figures 9a, b)

Pninaella (?) *pulchella* Parker, 1952, Bull. Mus. Comp. Zoöl., vol. 106, no. 9, p. 420, pl. 6, figs. 18a, b, 19, 20.

This species occurs at low percentages in the transition area of facies 3.

POROEPONIDES LATERALIS (Terquem)

(Plate 5, figures 6a, b)

Rosalina lateralis Terquem, 1878, Mém. Soc. Géol. France, sér. 3, vol. 1, Mém. 3, p. 25, pl. 2, figs. 11a-c.

This form is found in all facies except facies 1, occurring most abundantly in facies 3A south of the Thames River and Fishers Island, where it forms as much as 28 per cent of the fauna. It is an attached form and follows the same pattern of occurrence as the other attached forms found in the area, being confined to sandy and stony sediments.

PROTEONINA ATLANTICA Cushman

(Plate 1, figures 1, 2)

Proteonina atlantica Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 5, pl. 1, fig. 4.

P. atlantica occurs in facies 2 and 3. In facies 2 it is confined to the central part of Long Island Sound where it occurs at very low percentages. The highest percentages are found in facies 3, reaching a maximum of 61 per cent. The species is widely distributed on the continental shelf and adjacent slope south of Cape Cod where it is listed by Parker (1948, p. 239) as *P. difflugiformis* (combined with "*Reophax scorpiurus* Montfort").

PROTEONINA HANCOCKI Cushman and McCulloch

(Plate 1, figure 3)

Proteonina hancocki Cushman and McCulloch, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 3, p. 76.

Proteonina compressa Cushman and McCulloch (not Paalzow), 1939, Allan Hancock Pacific Exped., vol. 6, no. 1, p. 42, pl. 1, fig. 10.

This species occurs in facies 1 in the Connecticut River, with one occurrence in the Housatonic River, forming as much as 20 per cent of the fauna. The only previous report is from its type locality at Ketchikan, Alaska, at a depth of 15 m.

PROTEONINA LAGENARIUM (Berthelin)

(Plate 1, figures 4, 5)

Haplophragmium lagenarium (Berthelin), 1880, Mém. Soc. Géol. France, ser. 3, vol. 1, no. 5, p. 21, pl. 4, figs. 2a, b.

P. lagenarium is relatively abundant in facies 1 in the Connecticut River and occurs at lower percentages in facies 2 along the Connecticut shore. Many reports of this species are not reliable.

PROTEONINA sp. A

(Plate 1, figure 6)

This species occurs at very low percentages in facies 2 in the central area of Long Island Sound and in Buzzards Bay. It is smaller than *P. atlantica,* less contracted at the apertural end, and more finely arenaceous. It is possible that it is a variant of that species occurring in environments at the limits of its tolerance.

PROTEONINA sp. B

(Plate 1, figure 7)

This is probably a new species but is not found in sufficient numbers to warrant description. It is very small, being less than 0.2 mm. in length. It occurs in facies 1, in the Connecticut River.

PSEUDOPOLYMORPHINA NOVANGLIAE (Cushman)

(Plate 3, figures 11, 12)

Polymorphina lactea (Walker and Jacob) var. *novangliae* Cushman, 1923, Bull. 104, U. S. Nat. Mus., pt. 4, p. 146, pl. 39, figs. 6–8.

This species occurs at low percentages in all facies except facies 1. It does not occur in Long Island Sound except at a few isolated localities. The consistent occurrence is found in Gardiners Bay and the areas to the north and east and in Buzzards Bay. It is probable that the reference to *Guttulina lactea* in this region refers to young forms of *P. novangliae.* The species is found in all facies on the continental shelf and adjacent slope to the south but is almost entirely confined to depths less than 300 m. (Parker, 1948, p. 238).

PYRGO STRIATELLA (Cushman)

(Plate 2, figure 12)

Biloculina ringens (Lamarck) var. *striatella* Cushman, 1908, Proc. Boston Soc. Nat. Hist., vol. 34, p. 25, pl. 5, fig. 1.

P. striatella occurs in facies 3, being most common in the transition area where it reaches a frequency of 2 per cent. It is found at depths of less than 90 m. on the adjacent continental shelf (Parker, 1948, p. 222).

QUINQUELOCULINA SEMINULA (Linné)

(Plate 2, figures 7a, b)

Serpula seminulum Linné, 1758, Syst. Nat., ed. 10, p. 786.

This species occurs in all facies except facies 1. It reaches its most regular and abundant occurrence in facies 3A where it forms as much as 8 per cent of the fauna. It is not found in the western part of Long Island Sound. There seems to be some tendency for the species to be confined to sandy areas although this is not consistently true. It is confined to depths of less than 90 m. on the adjacent continental shelf (Parker, 1948, p. 221).

QUINQUELOCULINA SEMINULA (Linné) var. JUGOSA Cushman

(Plate 2, figures 8a, b)

Quinqueloculina seminula (Linné) var. *jugosa* Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res. p. 13, pl. 2, fig. 15.

This form is found in all facies except facies 1, but does not occur in Long Island Sound west of sta. 96. It is most common in facies 3A where it reaches frequencies of 5 per cent. It occurs chiefly on sandy or stony bottoms. On the adjacent continental shelf it occurs at depths of less than 90 m. (Parker, 1948, p. 222).

QUINQUELOCULINA SUBROTUNDA (Montagu)

(Plate 2, figures 9a, b, 10a, b)

"Serpula subrotunda dorso elevato" Walker and Boys, 1784, Test. Min., p. 2, pl. 1, fig. 4.

Vermiculum subrotundum Montagu, 1803, Test. Brit., pt. 2, p. 521.

This species occurs in all facies except facies 1. It is most abundant in facies 3A where it forms as much as 10 per cent of the fauna. Its occurrence in facies 2 is very slight and follows the same pattern as that of the other attached forms. Cushman, (1944, p. 15) refers to this species as *Quinqueloculina disciformis* (Macgillivray) and points out that in this area it is commonly found attached to algae and hydroids.

REOPHAX CURTUS Cushman

(Plate 1, figure 18)

Reophax curtus Cushman, 1920, Bull. 104, U. S. Nat. Mus., pt. 2, p. 8, pl. 2, figs. 2, 3.

R. curtus is confined to facies 3. It is found on the adjacent continental shelf but no depth limits of occurrence are reported.

REOPHAX DENTALINIFORMIS H. B. Brady

(Plate 1, figure 19)

Reophax dentaliniformis H. B. Brady, 1881, Quart. Jour. Micr. Sci., vol. 21, p. 49; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 293, pl. 30, figs. 21, 22.

This form is found in facies 2 at low percentages. This does not agree with the distribution of the species in other localities where it is reported to depths of 4300 m. A possible explanation of this may be that in facies 2 the species is almost entirely confined to sediments containing mud, and mud bottoms are relatively infrequent in facies 3.

REOPHAX NANA Rhumbler

(Plate 1, figures 14, 15)

Reophax nana Rhumbler, 1913, Ergeb. Plankton-Exped. Humboldt Stiftung, bd. 3, pt. 2, p. 471, pl. 8, figs. 6–12.

Reophax sp. ?, Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 10, pl. 1, fig. 20.

R. nana is most common in facies 2 in Buzzards Bay, where it composes as much as 9 per cent of the fauna. It occurs very rarely in facies 2 in Long Island Sound, mostly in Gardiners Bay, and in facies 3 in the vicinity of Cuttyhunk.

ROTALIA BECCARII (Linné) and variants

(Plate 5, figures 5a, b, 7a, b, 8a, b)

Nautilus beccarii Linné, 1758, Syst. Nat., ed. 10, p. 710.

This species occurs in facies 2 and 3. Although it is found along the Connecticut shore it occurs only at a few stations in the eastern part of central Long Island Sound. It is most abundant in facies 3A and in Buzzards Bay (facies 2) reaching maximum frequencies of 33 per cent. The relative abundance decreases in the well-developed portion of facies 3 and the occurrence is less persistent. A variant similar to *R. beccarii* var. *tepida* Cushman is found in facies 2 and at one station in facies 3A. Another variant referable to *R. beccarii* var. *sobrina* Shupack is found more persistently in facies 2 and at 3 stations in facies 3A.

The frequency of *R. beccarii* fluctuates greatly from station to station. These fluctuations cannot be definitely traced to sedimentary changes. In some areas the frequency falls in muddy sediments adjacent to sand but in others the mud samples contain a high percentage of the species.

TEXTULARIA cf. TENUISSIMA Earland[1]

(Plate 2, figures 4, 5)

Textularia tenuissima Earland, 1933, Discovery Repts., vol. 7, p. 95, pl. 3, figs. 21–30.

Textularia elegans Lacroix, 1932 (not *Plecanium elegans* Hantken), Bull. Instit. Ocean. Monaco, no. 591, p. 8, text. figs. 4, 6.

This form is tentatively referred to Earland's although it differs to some extent. At some stations in Gardiners Bay it is very irregular in form and has a much greater thickness (0.1 mm. or more). The wall of all the specimens is less smoothly finished than indicated by Earland and is colored by ferruginous material. In this respect it more closely resembles Lacroix's species from the Mediterranean which is included by Earland with his species from South Georgia.

The species occurs most commonly in Buzzards Bay but is present at occasional localities in facies 2 and 3 throughout the rest of the area. It never forms more than 2 per cent of the fauna and usually much less.

TRILOCULINA BREVIDENTATA Cushman

(Plate 2, figures 11a, b)

Triloculina brevidentata Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 16, pl. 2, fig. 25.

This species occurs in facies 2 in Gardiners Bay and Buzzards Bay. The specimens are smaller than those described by Cushman, being usually less than 1 mm. in length. In other respects they are identical with his type specimens.

TROCHAMMINA COMPACTA n.sp.

(Plate 2, figures 13a, b, 14a, b, 15a, b)

Trochammina conica Cushman (not Earland), 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 18, pl. 2, fig. 9.

Test small, concavo-convex, often with a high, trochoid spire which is broad and not pointed, composed of 3–4 whorls, thickness of test

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[1] *T. tenuissima* Earland is preoccupied by *T. tenuissima* Häusler 1881. The new name *Textularia earlandi* is proposed for Earland's species.

2/5 to 4/5 of diameter, ventral side concave, sometimes with a deep umbilicus; periphery rounded, narrow, slightly lobulate; chambers 3–4 in the adult whorl but most commonly 3, slightly inflated on the ventral side, less so on the dorsal side; spiral suture usually distinct, others often obscure, straight in early chambers, oblique, slightly curved, in adult chambers; wall slightly rough, composed of medium-sized sand grains; aperture a narrow arched opening at the base of the chamber. Maximum diameter 0.26 mm.

Holotype from sta. 199 in Buzzards Bay at a depth of 12 m., Lat. 41° 36.5′ N, Long. 70° 45.1′ W.

This species differs from *T. conica* Earland in the less inflated chambers, which in the latter species are almost globular and inflated on both sides of the test, in the almost non-lobulate periphery, and the more compressed test. It occurs in facies 2 and 3. In Long Island Sound the occurrence is confined to the central portion and Gardiners Bay. The most abundant and consistent occurrence is in Buzzards Bay where it forms a maximum of 10 per cent of the fauna.

TROCHAMMINA INFLATA (Montagu)

(Plate 3, figures 1a, b)

Nautilus inflatus Montagu, 1808, Test. Brit., Suppl., p. 81, pl. 18, fig. 3.

This species has a very scattered distribution. It is found in facies 1 at 3 stations in the Connecticut and Housatonic Rivers; in facies 2 at sta. 36 off the Connecticut shore, and sta. 205 and 206 at the head of Buzzards Bay; in facies 3A at sta. 160 and 161 northwest of Cuttyhunk. In all cases the species forms a very low percentage of the fauna. Phleger and Walton (1950, p. 280) found *T. inflata* in great abundance in Barnstable marsh. In the adjacent traverses in Cape Cod Bay the occurrence was very sparse and entirely in the traverse opposite the harbor outlet. These specimens were probably washed out of the marsh by tidal currents. In all cases the specimens found outside of facies 1 in the Long Island Sound-Buzzards Bay area are at nearshore stations and probably were also washed from neighboring marshes. Reported occurrences in the literature do not contradict the hypothesis that this is a marsh species.

TROCHAMMINA LOBATA Cushman

(Plate 3, figures 2a, b)

Trochammina lobata Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 18, pl. 2, fig. 10.

This is a widely distributed species in facies 2 and 3 (one exception). The highest frequencies are in facies 3 and at occasional stations in facies 2 in Buzzards Bay, with a maximum of 8 per cent. It is found at depths of less than 90 m. on the adjacent continental shelf (Parker, 1948, p. 221).

TROCHAMMINA MACRESCENS H. B. Brady

(Plate 3, figures 3a, b)

Trochammina inflata (Montagu) var. *macrescens* H. B. Brady, 1870, Ann. Mag. Nat. Hist., ser. 4, vol. 6, p. 51, pl. 11, figs. 5a-c.

T. macrescens has a similar distribution to *T. inflata* although it is more abundant in the Connecticut River, reaching a frequency of 16 per cent. It is found at three stations outside of facies 1: sta. 79, 160, 205. These occurrences have very low frequencies and it is probable that the specimens were washed from neighboring marshes as in the case of *T. inflata*. This species resembles *Jadammina polystoma* Bartenstein and Brand, but has a typical *Trochammina* aperture.

TROCHAMMINA SQUAMATA Parker and Jones, and related species

(Plate 3, figures 4a, b, 5a, b)

Trochammina squamata Parker and Jones, 1865, Phil. Trans. Roy. Soc. London vol. 155, p. 407, pl. 15, figs. 30, 31a-c.

Trochammina propria Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 19, pl. 2, fig. 11.

Representatives of this group are found in small quantities in all facies. It is probable that there are several species and/or variants, but in view of their scarcity it has not seemed feasible to subdivide them. The two most important representatives of the group are *T. squamata* as originally figured by Parker and Jones, which is apparently identical to Cushman's *T. propria*, and *T. ochracea* (Williamson).

URNULINA COMPRESSA Cushman

(Plate 1, figure 9)

Urnulina compressa Cushman, 1930, Bull. 4, Florida State Geol. Surv., p. 15, pl. 1, figs. 2a, b.

This species occurs at frequencies as great as 13 per cent in facies 1 in the Connecticut River, but occurs at only one station in the

Housatonic River. A single specimen is reported from the mouth of the Merrimack River (Parker, 1952 p. 394) north of Cape Cod. The species is variably spinose at the base, although not originally so described.

URNULINA DIFFLUGAEFORMIS Gruber

(Plate 1, figure 10)

Urnulina difflugaeformis Gruber, 1884, Nova. Acta k. Leop.-Carol. Deutsch. Ak. Nat., vol. 46, p. 496, pl. 8, fig. 18.

This species occurs at low frequencies in facies 1 in the Connecticut River.

VIRGULINA FUSIFORMIS (Williamson)

(Plate 4, figure 6)

Bulimina pupoides d'Orbigny var. *fusiformis* Williamson, 1858, Rec. Foram. Great Britain, p. 63, pl. 5, figs. 129, 130.

This species occurs at very low frequencies throughout facies 3 and at occasional stations in facies 2 in Buzzards Bay. It occurs in all facies on the continental shelf and adjacent slope (Parker, 1948, p. 240).

CONCLUSIONS

1. There are three Foraminiferal facies in the Long Island Sound-Buzzards Bay area: 1) river facies, 2) bay facies, 3) shallow-water, open-ocean facies.
2. There is evidence that the Foraminifera of the river facies are mixed with those of marsh facies washed in by tidal currents. Mixing also occurs at other facies boundaries.
3. Temperature appears to be an important controlling factor in the change from bay to open-ocean Foraminifera facies. Salinity appears to be an important controlling factor in the change from river to bay Foraminifera facies. It is probably less important in the change from bay to open-ocean Foraminifera facies.
4. Attached forms are best developed on sandy and stony bottoms. There is little indication of sedimentary control of other species.

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Contribution No. 590, Woods Hole Oceanographic Institution.

Table 1

Locations of stations giving depth and type of sediment.

Station No.	*N. Latitude*	*W. Longitude*	*Depth in Meters*	*Type of Sediment*
1	41°23.6′	72°25.0′	6	sand
2	41°23.3′	72°24.4′	5	sand
3	41°23.3′	72°23.8′	7.5	sand
4	41°23.1′	72°23.3′	3	sand
5	41°22.8′	72°22.7′	11.5	sand
6	41°22.3′	72°22.5′	4.5	sand
7	41°21.8′	72°22.7′	7	sand
8	41°21.3′	72°22.7′	3	sand
9	41°21.1′	72°23.1′	—	silt
10	41°20.8′	72°22.7′	4.5	sand
11	41°20.3′	72°21.6′	8	sand
12	41°19.9′	72°21.2′	2.5	sand
13	41°19.8′	72°20.8′	3	sand
14	41°19.4′	72°20.7′	5	silt
15	41°18.9′	72°20.8′	5	silt
16	41°18.4′	72°21.0′	5.5	sand
17	41°17.9′	72°20.9′	4	sand
18	41°17.4′	72°20.9′	3.5	sand
19	41°16.9′	72°20.7′	5	sand
20	41°16.5′	72°20.5′	12	sand
21	41°15.9′	72°19.6′	2	sand
22	41°15.8′	72°18.9′	4	sand
23	41°15.6′	72°18.3′	4	sand
24	41°15.4′	72°21.8′	6.5	sand and mud
25	41°15.0′	72°22.8′	10	sand
26	41°14.9′	72°24.3′	15	sand and mud
27	41°14.7′	72°25.6′	17	sand
28	41°14.7′	72°27.0′	20	sand
29	41°14.5′	72°28.2′	20	sand
30	41°14.3′	72°29.5′	10	sand
31	41°14.1′	72°32.2′	10	sand
32	41°14.0′	72°33.3′	15	sand and mud
33	41°13.8′	72°34.7′	15	—
34	41°13.7′	72°36.1′	15	sand
35	41°13.6′	72°37.4′	14	fine sand
36	41°13.5′	72°38.7′	14	sand
37	41°13.4′	72°40.0′	12	fine sand
38	41°13.4′	72°41.3′	12	sand
39	41°13.3′	72°42.6′	10	sand and stones
40	41°13.3′	72°43.9′	12	fine sand
41	41°13.3′	72°45.2′	12	mud
42	41°13.3′	72°46.6′	11	sand and mud

Station No.	*N. Latitude*	*W. Longitude*	*Depth in Meters*	*Type of Sediment*
43	41°13.3′	72°47.8′	9	sand and mud
44	41°13.1′	72°49.2′	10.5	sand and mud
45	41°12.8′	72°50.5′	12	sand and mud
46	41°12.5′	72°51.8′	—	—
47	41°12.3′	72°53.1′	14	sand and mud
48	41°12.0′	72°54.4′	10.5	sand and mud
49	41°11.7′	72°55.8′	11	sand
50	41°11.4′	72°57.1′	12	sand
51	41°11.1′	72°58.4′	12	sand and mud
52	41°10.9′	72°59.8′	11	mud
53	41°10.6′	73°01.1′	9	sand and mud
54	41°10.3′	73°02.4′	9	sand and mud
55	41°10.0′	73°03.8′	9	sand and mud
56	41°09.7′	73°05.0′	7	sand and mud
57	41°09.8′	73°06.1′	3	sand and stones
58	41°10.1′	73°06.5′	2	—
59	41°10.9′	73°07.3′	3	silt
60	41°11.3′	73°07.2′	5	sand
61	41°11.7′	73°06.7′	4	sand
62	41°12.3′	73°06.6′	4	sand
63	41°12.7′	73°06.6′	4	sand
64	41°13.3′	73°06.5′	2	sand
65	41°09.1′	73°05.6′	6.5	black mud
66	41°08.1′	73°05.7′	10	black mud
67	41°07.1′	73°05.8′	13	black mud
68	41°06.0′	73°05.9′	13	sand and mud
69	41°05.0′	73°05.9′	18.5	sand and mud
70	41°04.0′	73°05.8′	7	stony
71	41°03.7′	73°05.4′	15	sand
72	41°03.9′	73°04.1′	22.2	sand and mud
73	41°04.1′	73°02.8′	27	mud
74	41°04.4′	73°01.5′	28.5	mud
75	41°04.5′	73°00.2′	27.5	mud
76	41°04.8′	72°58.8′	27.5	sand and mud
77	41°04.9′	72°57.5′	24	sand and mud
78	41°05.2′	72°56.2′	29	mud
79	41°05.4′	72°54.9′	29	mud
80	41°05.6′	72°53.6′	29	mud
81	41°05.8′	72°52.2′	27.5	sand and mud
82	41°05.9′	72°50.9′	28	mud
83	41°06.1′	72°49.5′	28	mud
84	41°06.3′	72°48.3′	28	sand and mud
85	41°06.4′	72°46.9′	29	silt
86	41°06.6′	72°45.6′	28.5	fine sand
87	41°06.7′	72°44.2′	28.5	sand and mud

Station No.	*N. Latitude*	*W. Longitude*	*Depth in Meters*	*Type of Sediment*
88	41°06.8′	72°42.9′	27.5	sand and mud
89	41°07.0′	72°41.5′	28	sand and mud
90	41°07.2′	72°40.2′	27	fine sand
91	41°07.3′	72°38.8′	27	sand and mud
92	41°07.5′	72°37.5′	26	—
93	41°07.7′	72°36.1′	24	sand
94	41°07.8′	72°34.9′	21	sand
95	41°07.9′	72°33.5′	21.5	sand
96	41°08.1′	72°32.1′	26	sand
97	41°08.3′	72°30.8′	27	sand
98	41°09.3′	72°30.4′	20	sand
99	41°09.5′	72°13.4′	8	sand
100	41°08.4′	72°13.6′	8	sand and mud
101	41°07.3′	72°13.7′	11	sand and mud
102	41°06.4′	72°13.8′	10.5	sand and mud
103	41°05.3′	72°13.9′	10.5	mud
104	41°04.3′	72°14.0′	8	sand and mud
105	41°03.4′	72°14.1′	5	sand
106	41°03.8′	72°12.7′	11	sand and mud
107	41°04.2′	72°11.5′	9	sand and mud
108	41°04.6′	72°10.3′	4.5	sand
109	41°05.6′	72°10.0′	10	sand and mud
110	41°06.6′	72°09.7′	9	silt
111	41°07.6′	72°09.3′	13	fine sand
112	41°08.6′	72°08.9′	25	sand
113	41°09.6′	72°08.4′	28	sand and mud
114	41°10.5′	72°07.9′	7.5	sand
115	41°11.5′	72°07.6′	7	sand, stones
116	41°17.8′	72°04.4′	11	mud
117	41°16.9′	72°04.0′	15	mud
118	41°16.0′	72°03.5′	20	mud
119	41°15.2′	72°04.4′	37	mud
120	41°15.1′	72°05.0′	61	mud
121	41°15.0′	72°06.1′	61	sand
122	41°14.8′	72°06.9′	61	sand
123	41°14.6′	72°08.2′	67	sand
124	41°14.4′	72°06.1′	76	sand
125	41°14.1′	72°03.8′	61	sand
126	41°15.4′	71°59.3′	12	sand
127	41°15.7′	71°58.8′	9	sand
128	41°15.9′	71°58.1′	15	sand
129	41°16.1′	71°57.4′	15	sand
130	41°16.3′	71°56.8′	14	sand
131	41°16.5′	71°56.1′	14	sand
132	41°16.7′	71°55.5′	12	sand

Station No.	*N. Latitude*	*W. Longitude*	*Depth in Meters*	*Type of Sediment*
133	41°16.5′	71°54.6′	24	stony
134	41°16.6′	71°53.5′	37	sand
135	41°16.5′	71°52.3′	40	sand
136	41°16.6′	71°50.5′	40	sand
137	41°16.6′	71°49.0′	42	mud
138	41°16.7′	71°47.5′	42	mud
139	41°16.7′	71°46.0′	36	mud
140	41°16.7′	71°44.5′	36	sand
141	41°16.7′	71°43.1′	37	mud
142	41°16.8′	71°41.6′	37	mud
143	41°16.8′	71°40.1′	38	mud
144	41°16.8′	71°38.7′	37	mud
145	41°16.9′	71°37.2′	38	sand
146	41°16.9′	71°34.3′	41	sand
147	41°17.0′	71°32.6′	43	mud
148	41°15.8′	71°32.2′	43	sand
149	41°14.8′	71°31.9′	24	sand
150	41°13.8′	71°31.6′	38	sand
151	41°11.8′	71°32.5′	21	stony
152	41°15.8′	71°55.4′	46	stony
153	41°15.4′	71°54.9′	49	sand
154	41°14.8′	71°54.1′	41	sand
155	41°14.1′	71°54.3′	43	sand
156	41°13.3′	71°54.4′	40	sand
157	41°12.3′	71°55.5′	30	sand
158	41°11.5′	71°56.1′	55	sand
159	41°10.6′	71°57.0′	21	sand
160	41°26.7′	71°07.8′	20	sand and stones
161	41°27.0′	71°05.2′	11	sand and stones
162	41°27.3′	71°02.6′	14	sand and stones
163	41°27.5′	71°01.2′	17	sand and stones
164	41°27.3′	71°00.6′	17	sand
165	41°27.6′	70°59.4′	24	sand
166	41°27.9′	70°58.2′	29	sand
167	41°28.3′	70°56.9′	27	sand
168	41°26.9′	71°00.3′	18	sand
169	41°25.8′	71°02.4′	18	sand
170	41°24.6′	71°04.4′	20	sand
171	41°24.3′	71°05.7′	21	sand
172	41°23.7′	71°06.8′	22	sand
173	41°23.1′	71°07.9′	24	sand
174	41°22.4′	71°08.9′	27	sand
175	41°21.7′	71°10.1′	28	sand
176	41°27.0′	70°59.4′	18	mud, sand, stones
177	41°26.4′	70°59.5′	27	sand and mud

Station No.	*N. Latitude*	*W. Longitude*	*Depth in Meters*	*Type of Sediment*
178	41°25.6′	70°59.7′	34	mud
179	41°24.7′	70°59.9′	33	mud
180	41°23.8′	71°00.1′	33	mud
181	41°22.8′	71°00.3′	30	mud
182	41°21.8′	71°00.1′	28	mud
183	41°20.8′	71°00.2′	28	sand
184	41°19.8′	71°00.3′	27	sand
185	41°18.8′	71°00.9′	33	sand
186	41°17.9′	71°01.5′	37	mud
187	41°32.9′	70°45.2′	15	sand and mud
188	41°33.4′	70°46.4′	15	mud
189	41°33.8′	70°47.6′	15	mud
190	41°34.2′	70°48.8′	9.5	sand
191	41°34.2′	70°46.9′	14.5	sand and mud
192	41°34.3′	70°45.5′	12.5	sand
193	41°34.4′	70°44.1′	13	sand and mud
194	41°34.4′	70°42.9′	13	sand and mud
195	41°34.5′	70°41.5′	13	sand
196	41°34.5′	70°40.3′	4.5	sand and stones
197	41°35.1′	70°41.4′	16	mud
198	41°36.2′	70°44.0′	12.5	sand and mud
199	41°36.5′	70°45.1′	12	sand and mud
200	41°37.0′	70°46.3′	12	sand and mud
201	41°37.7′	70°45.4′	13	mud
202	41°38.4′	70°44.4′	9.5	sand and mud
203	41°39.0′	70°43.5′	9	sand and mud
204	41°39.6′	70°42.5′	7	sand and mud
205	41°40.4′	70°41.7′	8	sand and mud
206	41°41.0′	70°40.8′	8	sand

STATION NO.	5	7	8	9	12	13	14	15	16	18	19	20	21	22	23	24	25	26	27	29	30	31	32	34	35	36	37	39	40	41	43
Ammoastuta salsa						10		1				.7				.5				.3		.2									
Ammobaculites cf. exiguus						4		1			13																				
Ammoscalaria fluvialis						2						.7			1																
Bolivina variabilis																.9						.2				.2					
Cibicides lobatulus																						.2									
Discorbis columbiensis																.5	.3	1						.6		.2					
Eggerella advena						.9	5	13				1	6		1	4	.6	2		5	1	.5	.5		.9	1	.3	.2	2	1	.9
Elphidium advenum																					.2										
E. advenum var. margaritaceum												.7					.3														
E. excavatum																			.7	.5	.2			.6			.1		.2		
E. incertum & variants								3				10	75	36	81	54	89	81	88	65	86	85	72	91	79	75	86	68	75	85	90
E. subarcticum																2	2	5	1	9	3	3	6	2	5	4	2	6	2	2	2
Eponides frigidus var. calidus												2			3	3	3	4	5	14	8	9	19	2	13	17	11	22	21	11	7
E. wrightii																									.3						
Hopkinsina pacifica atlantica																												.2			
Lagunculina vadescens		1														.5															
Leptodermella variabilis		21	30	6		8	16	1				7			1	3															
Miliammina fusca				11				9	40	33	37	3	6	[illegible]	1	4								1		.2			.2		
Nonion tisburyensis												3	[illegible]	9	3	.9		.3	.7	.5	.2		.8	.6	.6	.8	.3	.2	.3	.7	
Poroeponides lateralis																.5		.3													
Proteonina hancocki		20	10	5		12	5	12				7			3	2															
P. lagenarium	100	40	20	60	100	21	42	40	40	33	13	31			3	16	.6			.8	.2	.2	5		3	.2			3		
P. sp. B.		7	10	1		.9						3																			
Pseudopolymorphina novangliae																				.3								.2			
Quinqueloculina seminula																	1	.3	2									2			
Q. seminula var. jugosa																	9	7	.7		.2										
Q. subrotunda																.5	1	2	1		.2							.5			
Rotalia beccarii																		.3		.3		.5	.3	.6	.3		.6				
R. beccarii var. tepida																							.3								.2
Textularia cf. tenuissima								1													.2										
Trochammina inflata								1																		.2					
T. lobata															1			.3						.6	.3						
T. macrescens						4	16	1				10																			
T. squamata		1	20	5		3	5	10	20	33	13	5		46	1	2		2		4		1	.3		.6	.3	.3	.7	.2		
Urnulina compressa		10	10	8		7	11	6			13	11	6		1	4															
U. difflugaeformis				4		4					13	3				2															
TOTAL POPULATION	2	85	10	80	2	110	20	80	6	3	8	150	16	11	80	210	650	750	150	750	1000	13300	3000	2600	10800	5000	22000	425	10700	3300	3800

Table 2. Percentage distribution of Foraminifera at sta. 5–43.

STATION NO.	45	47	48	50	52	53	55	56	57	58	59	60	61	62	63	64	65	66	68	70	71	72	73	75	76	78	80	82	84	85	86	88
Ammoastuta salsa			.1																													
Ammobaculites cf. exiguus											18																					
Ammoscalaria fluvialis											75						.1															
Bolivina variabilis						.1																										
Discorbis columbiensis																							.1								.2	
Eggerella advena	.4	.4	1	.9	1	5	1	1										.3	.3	.9	7	7	21	7	6	9	12	15	27	9	17	19
Elphidium advenum													5																			
E. advenum var. margaritaceum																					.2											
E. excavatum	.1																												.4			
E. incertum & variants	81	76	79	86	85	75	84	88	85	32	2	50	37	50	41	33	98	96	94	86	56	46	37	66	66	57	41	43	39	55	45	50
E. subarcticum	3	3	4	3	2	3	2	.4	3		.6		32		14		.3	.2	.8	5	13	5	4	3	6	10	5	10	5	4	2	5
Eponides frigidus var. calidus	16	20	15	10	11	17	12	9	9	33			21		45	33	1	3	4	9	23	41	35	22	21	21	41	29	24	28	29	25
E. wrightii																				.3												
Hopkinsina pacifica atlantica																											.4				.4	
Leptodermella variabilis														50																		
Miliammina fusca									1		.6																					
Nonion tisburyensis	.5	.4			.2																											
Proteonina atlantica																						.1					.4					2
P. hancocki												50																				
P. sp. A																												.5	.2	.4	.2	
Pseudopolymorphina novangliae																										.2						
Quinqueloculina seminula																					.2											
Reophax dentaliniformis				1		.3	.2											.3				.2	.3	.6	.2	.8			2	.2	1	
R. nana				1																									.2			
Rotalia beccarii					1			.2																								
R. beccarii var. tepida	1	.1																														
Textularia cf. tenuissima				.1				2															1						4		2	
Trochammina compacta																														4	.2	
T. inflata										33						33																
T. lobata				.1																	.5											
T. macrescens											2																					
T. squamata	1	1	1			1		4			2		5					.3			.2	.3	1	3	2	2	4	3	3	3	4	1
Urnulina compressa											.6																					
TOTAL POPULATION	4300	5400	13000	43000	14100	5500	14000	1500	69	3	270	2	19	2	22	3	50000+	50000+	2700	1300	2200	1800	700	2800	1000	475	1000	1500	2000	3800	1900	800

Table 3. Percentage distribution of Foraminifera at sta. 45–88.

STATION NO.	89	90	92	93	94	95	97	99	100	102	103	105	106	108	110	112	113	114	116	117	118	119	121	122	123	125	127	129	130	131	132	134
Ammoastuta salsa																			4													
Ammobaculites cf exiguus																					3											
A. cf. foliaceus																				1	1	4										
Ammoscalaria fluvialis																					7											
Bolivina pseudoplicata			2														8						6	3		1		.6	5	3	1	1
B. variabilis												2	.2	2			.3	.3							6	6	1	6			.8	.6
Bulimina aff. aculeata																				2				.3				3	.5	3	4	3
Cibicides concentricus																														3	2	
C lobatulus	3		3	3	3	10										1	1	2	4	.8		2	5	4	3	3	1	4	8	6	9	8
Discorbis columbiensis		2	9	1	1		19	2		1				2		3	7	28		6		1	9	10	9	12	28	24	18	9	19	11
D. squamata																								.7		2	1	3			.2	7
Eggerella advena	19	10	6	7	15	10	4	6	4	3	4	7	2	.2	4	4	14	5	13	6	7	5	5	2	2	7	15	3	4	1	5	6
Elphidium advenum								7				2		4		1	1	.3					6			6	1	2	1	1	2	.7
E. advenum var margaritaceum		4	5	2	1					.1		3	1	6		3	.6	1		.8	.3		6	.3			1	1	5	3	1	1
E. excavatum				5										6	.5	.8																
E. incertum & variants	47	61	67	47	39	40	15	32	70	77	70	33	70	30	70	40	32	14	65	60	58	48	17	10	18	11	6	16	22	13	22	24
E subarcticum	2	5	16	24	23	20	23	45	3	4	10	34	11	38	6	32	31	19	4	11	8	18	24	13	7	1.1	4	18	15	27	15	23
Eponides frigidus																	6							.5		6		2	1	3	8	4
E frigidus var. calidus	27	20	8	5	11		4	8	18	13	14	7	8	5	11	7	2	1	2	5	3	6	4	8	2	6		1	4	2	3	3
E. wrightii							2	3				2		10		3	9	7	.4					.5	.6		12	1	.5	5	6	3
Globulina caribaea			2	5			2																6	3					5	1		
Glomospira gordialis																								.3		5	1					
Hopkinsina pacifica atlantica		.2		2					.6		1				.5		.3															
Miliammina fusca																	.3				.3			3								
Nonion tisburyensis		2							.9	2	2	1	.5							1	1	3										
Nonionella atlantica																						4	6	.5	.6					3		.3
Pninaella pulchella																										.6	1	.9				
Poroeponides lateralis				5			4									.4	.9	4				.4	11	22	18	17	6	6	5	10	3	2
Proteonina atlantica	9	5	.8	3				.2											.4	4	1	2								1	1	1
P. sp. A	.3																															
Pseudopolymorphina novangliae									.1	.1	.1	2		.8					4	.2	1	.8			.6					.7		.3
Pyrgo striatella																						.8		.3	.6	1		.6	1	1	2	2
Quinqueloculina seminula												.5		.2																		
Q. seminula var. jugosa							.2	.2				9											1	2	.6			.3				
Q. subrotunda				2	3	5	2					2				2	6	15					10	9	9	3	4	2	5		2	2
Reophax dentaliniformis									.6	.8	5																					
R. nana									.4		4		.1		.5																	
Rotalia beccarii			.8	4	3	15		4	.8	6		9	4	2	.9	2	4	2	11	10	16	11	7	15	21	9		7	6	17	9	3
R. beccarii var. sobrina								.4	.6			.5		.8																		
R. beccarii var tepida											.3	.2	.1																			
Textularia cf. tenuissima	3	2						7					.1																			
Triloculina brevidentata								.2				5		.6																		
Trochammina compacta	.3	2	.2								.1	.2	.2						.4										.5	.3	.8	.3
T. lobata	.9		.6	1	1			.2				.5	1	.2		.4	.6	.3	1	1	1	2		.3				.3	2		.6	
T. squamata	2	1	1	7			23	.2	1	.4	5	.2	.1		.8		.5	3	7	.6	1		2	3	2	11	6	4	.5	.3	2	1
Virgulina fusiformis																						.4	.6		6	.6		.9	.5			1
TOTAL POPULATION	5100	2200	650	400	80	20	48	900	50000+	50000+	12400	6800	3700	2000	1700	525	350	2300														

Table 4. Percentage distribution of Foraminifera at sta. 89–134.

STATION NO.	135	136	138	140	142	143	145	146	147	148	150	151	152	153	155	157	158	159	160	162	163	165	166	168	169	171	172	174	175	177	179	181	182	183	184	185	186
Ammobaculites foliaceus	2	9	4	2	2	5	1			5			2	2												1	.3	9	3				.8		3		
Bolivina pseudoplicata	1					.5	.3		.3	.3	.7		.6		4					1			.2	9				.3	3		8	8	1	1	3		
B. variabilis																															.2	2					
Bulimina aff. aculeata						5	3						6										.2				.3	3					5				
Cibicides concentricus																					.4				2	7				1	2						
C. lobatulus	1	.9					1			3	2	8	1	5	2	6				2	2		1	2	3	1			3	2	2	6	1		3	5	
Discorbis columbiensis							1	.3		.3	7	8	.6		2	1	2			22	3	1	.2	5	3	2			3	6	5	2	2		3		
D. squamata																								.2												2	
Eggerella advena	15	13	28	18	44	45	3	37	39	33	34	2	5	21	13	6	6	3	15	12	1	7	6	7	9	11	40	37	11	6	11	15	11	9	23	5	13
Elphidium advenum																				1	.9		.2			.3					2	2	3				
E. advenum var. margaritaceum								1		.5	9									3			4	9		3				7	8	6			3		
E. excavatum																							4			2	3									2	
E. incertum & variants	31	36	25	31	19	16	24	23	20	16	4	6	42	46	58	66	66	54	40	27	26	78	67	44	26	45	14	30	19	38	55	58	50	56	50	27	19
E. subarcticum	11	8	4		2	9	14	4	9	8	5	2	21	6	11	11	10	8	3	1	18	3	10	17	29	7	6	6	3	10	8	5	4	9	2	2	2
Eponides frigidus	7	7	8	9	3	3	4	5	5	7	2	4	2	5	3	3										1		1			2	8	3		1		
E. frigidus var. calidus		2	1		1	1	7	1	3	1			1	3	3	2					2	3	2	2	3	1		1		1	1	2	2		1		
E. wrightii									3			6								1	4		2	2								2					
Globulina caribaea																2													3							2	
Glomospira gordialis																								7			.3									2	
Labrospira crassimargo			3	7	4	.5	2	2	2																												2
Miliammina fusca																										.3											
Nonionella atlantica														5	4	6																		1			
Paraeponides lateralis											2	25			4					13	3			2	2					2	2					2	
Proteonina atlantica	19	25	17	33	17	24	40	17	26	31	25	2	13	9	4	2	6		10		4	5	2			5	17	21	39	1	2	5	14	5	12	39	61
Pseudopolymorphina novangliae							.7							.5						.5				.4		3	7	3	6			.4	.3	1			
Pyrgo striatella							1				2	2				6					.4					7	.3			7	4		.3				
Quinqueloculina seminula	1	2					2	6	3			15	6				7		5	3	3		.4		2		.3			3				2	.3	2	
Q. seminula var jugosa		.9					3		.3									5		.5	3			.2		1											
Q. subrotunda								.6				2						5	3	5						.3	7						.3				
Reophax curtus		2	2	3	4	3	2	4	4	7	3		6															6				.2	5		.8		2
R. nana																			3							.3	.3					.2					
Rotalia beccarii	2	2	4	7	1	5	1				2		1	4	8	.6		18	10	5	33	5	10	16	18	16	13	2	6	25	13	7	4	9	2		
R. beccarii var. sobrina																							.2	2													
Textularia tenuissima			.9		.5			.3																.2													
Trochammina compacta	1		2	.7	1									.5										.2		.7	1					.2					
T. inflata																			5	2																	
T. lobata	1	3	.9	3	3	[illegible]	.7	9	.9	.5	4	2	7	1	2		2	3	3		1		.2		5	1	1	5	3		.6	2	1	4	5		
T. macrescens																			3																		
T. squamata	2		3			.9		.6	2	2			.6	.5	.8	3		5	3	1		.5		3			1	1					.5		.3	2	
Virgulina fusiformis	1					.5		.3		.3						.6						.5		.4							.2				.3		.5

Table 5. Percentage distribution of Foraminifera at sta. 135–186.

STATION NO.	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206
Ammobaculites cf. dilitatus					.2						.1	.2		8	.8					
Bolivina pseudoplicata										.4						.4		.2		
B. variabilis				.2				.3												
Cibicides lobatulus				.6															1	.1
Discorbis columbiensis				.3				.2		.2						2	4	1	2	14
Eggerella advena	10	17	12	13	57	41	76	27	7	.4	29	74	66	49	10	11	2	2	7	6
Elphidium advenum				7				.2	6	24	.1					.7	1	5	5	1
E. advenum var. margaritaceum				3				.2		11							.7	.7	.5	7
E. excavatum				.4		.1		.6							.8	15	11	8	2	
E. incertum & variants	61	61	77	12	13	13	4	32	35	2	44	5	5	12	61	30	31	24	41	22
E. selseyense				1						11						2	.4	.7		1
E. subarcticum	20	16	6	16	13	19	13	25	16	2	4	6	6	20	13	13	5	5	23	11
Eponides frigidus var. calidus	2	2	2	2	2	1	1	2	7	1	2	.7	.8	2	4	3	3	6	4	8
E. wrightii				6						.7							.7			
Hopkinsina pacifica atlantica						.2		2								.9			.3	
Miliammina fusca											.1			.2	.1				.1	
Nonion tisburyensis								.4	.3		.3				4				.6	.9
Poroeponides lateralis				.6																
Proteonina sp. A			.9		.2	.1	.3	.2			2	5		3	1			.2	.3	
Pseudopolymorphina novangliae				.4		.9			2	1		.2		.2	.1	.4	1	1	.4	
Quinqueloculina seminula	.1			5		.2		.3	1	3							4	4		
Q. seminula var. jugosa				.6						.4								.7		
Reophax dentaliniformis											.2				.3	.2				
R. nana		.3	2		6	.6	.5	3			4	9	4	9	3	.4	4	1	2	
Rotalia beccarii				19	3	6		2	19	7	5		3	.3	.4	16	30	29	4	3
R. beccarii var. sobrina						.1	.3			1	3	.2	4			3				2
R. beccarii var. tepida					.2	.7		.7	1							3	2	1	.9	
Textularia tenuissima				.4	1		.3	.4	.3		1	.2		1	.1	.2			2	2
Triloculina brevidentata				6		6			.9	30						.2	2	4	4	2
Trochammina compacta	.7	2		.2	6	6	2	1	3		9	3	10	2		.2	2	2	3	1
T. inflata																			.6	2
T. lobata				2	.6	6	2	.9	8		.2	.2	5				7	.9	.6	4
T. macrescens																			.3	
T. squamata	1							.4			1	2	.2	3					2	3
Virgulina fusiformis								.2							.2	.2			.1	
TOTAL POPULATION	3000	600	850	450	1000	800	725	2500	625	275	16000	425	525	500	2900	3700	1100	1700	1600	100

Table 6. Percentage distribution of Foraminifera at sta. 187–206.

PLATE 1

Fig. 1, 2. *Proteonina atlantica* Cushman. X 50. (1) Sta. 145; (2) Sta. 93.

Fig. 3. *Proteonina hancocki* Cushman and McCulloch. X 70. Sta. 9.

Figs. 4, 5. *Proteonina lagenarium* (Berthelin). X 70. Sta. 24.

Fig. 6. *Proteonina* sp. *A*. X 70. Sta. 200.

Fig. 7. *Proteonina* sp. *B*. X 70. Sta. 9.

Fig. 8. *Lagunculina vadescens* Cushman and Bronnimann. X 70. Sta. 24.

Fig. 9. *Urnulina compressa* Cushman. X 70. Sta. 20.

Fig. 10. *Urnulina difflugaeformis* Gruber. X 70. Sta. 9.

Figs. 11a, b, 12. *Leptodermella variabilis* n.sp. X 70. (11) Holotype; (12) Paratype. Sta. 24.

Fig. 13. *Glomospira gordialis* (Jones and Parker). X 50. Sta. 168.

Figs. 14, 15. *Reophax nana* Rhumbler. X 70. Sta. 200.

Figs. 16, 17. *Ammobaculites* cf. *exiguus* Cushman and Bronnimann. X 70. Sta. 59.

Fig. 18. *Reophax curtus* Cushman. X 50. Sta. 174.

Fig. 19. *Reophax dentaliniformis* H. B. Brady. X 50. Sta. 101.

Figs. 20, 21. *Ammobaculites* cf. *foliaceus* (H. B. Brady). X 50. Sta. 171.

Fig. 22. *Labrospira crassimargo* (Norman). X 42. Sta. 186.

Fig. 23. *Ammobaculites* cf. *dilitatus* Cushman and Bronnimann. X 50. Sta. 200.

Figs. 24, 25. *Ammoscalaria fluvialis* n.sp. X 50. (24) Holotype; (25) Paratype. Sta. 59.

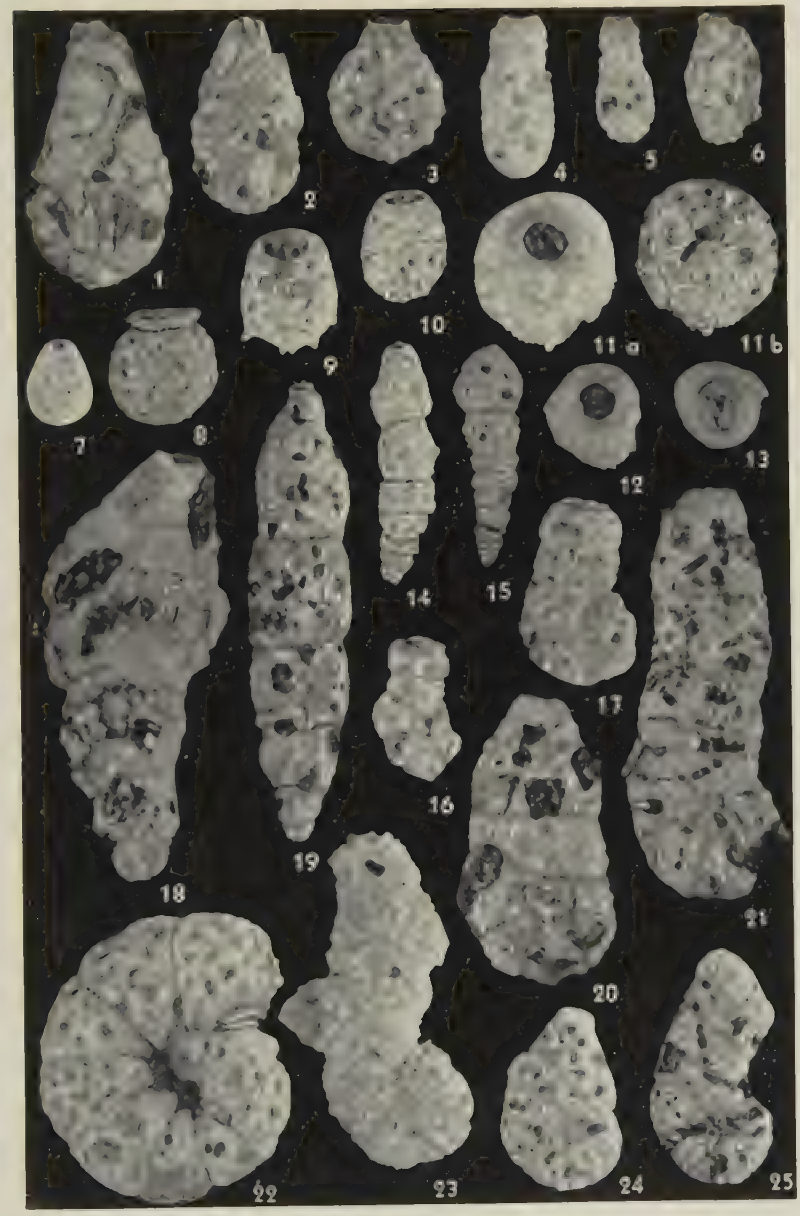
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PLATE 2

Figs. 1, 2. *Ammoastuta salsa* Cushman and Bronnimann. X 70. Sta. 13.

Fig. 3. *Eggerella advena* (Cushman). X 50. Sta. 111.

Figs. 4, 5. *Textularia* cf. *tenuissima* Earland. X 70. (4) Sta. 200; (5) Sta. 109. (see footnote, p. 458)

Figs. 6a, b. *Miliammina fusca* (H. B. Brady). X 70. Sta. 24.

Figs. 7a, b. *Quinqueloculina seminula* (Linné). X 50. Sta. 105.

Figs. 8a, b. *Quinqueloculina seminula* (Linné) var. *jugosa* Cushman. X 50. Sta. 105.

Figs. 9a, b, 10a, b. *Quinqueloculina subrotunda* (Montagu). X 50. Sta. 114.

Figs. 11a, b. *Triloculina brevidentata* Cushman. X 50. Sta. 105.

Fig. 12. *Pyrgo striatella* (Cushman). X 50. Sta. 180.

Figs. 13a, b, 14a, b, 15a, b. *Trochammina compacta* n.sp. X 70. (13) Holotype; (14, 15) Paratypes. Sta. 199.

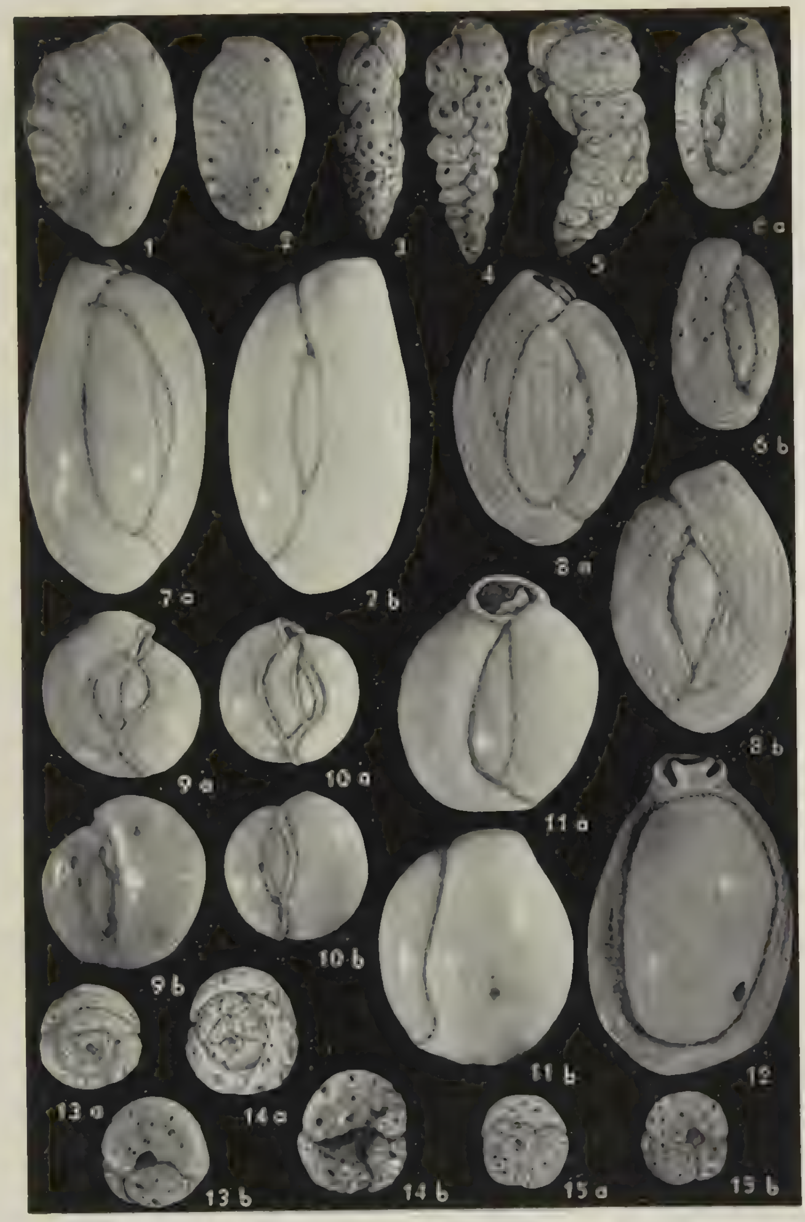
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PLATE 3

Figs. 1a, b. *Trochammina inflata* (Montagu). X 50. Sta. 64.

Figs. 2a, b. *Trochammina lobata* Cushman. X 50. Sta. 111.

Figs. 3a, b. *Trochammina macrescens* H. B. Brady. X 50. Sta. 14.

Figs. 4a, b. *Trochammina squamata* Parker and Jones. X 70. Sta. 111.

Figs. 5a, b. *Trochammina ochracea* (Williamson). X 70. Sta. 82.

Fig. 6. *Globulina caribaea* d'Orbigny. X 50. Sta. 130.

Figs. 7, 8. *Nonion tisburyensis* Butcher. X 50. (7) Sta. 105; (8) Sta. 100.

Fig. 9. *Elphidium advenum* (Cushman). X 70. Sta. 196.

Fig. 10. *Elphidium advenum* (Cushman) var. *margaritaceum* Cushman. X 50. Sta. 105.

Figs. 11, 12. *Pseudopolymorphina novangliae* (Cushman). X 50. (11) Sta. 196; (12) Sta. 204.

Fig. 13. *Elphidium excavatum* (Terquem). X 50. Sta. 201.

Figs. 14, 16, 17. *Elphidium incertum* (Williamson) variants. X 50. (14) Sta. 105; (16) Sta. 65; (17) Sta. 111.

Figs. 15a, b. *Nonionella atlantica* Cushman. X 50. Sta. 119.

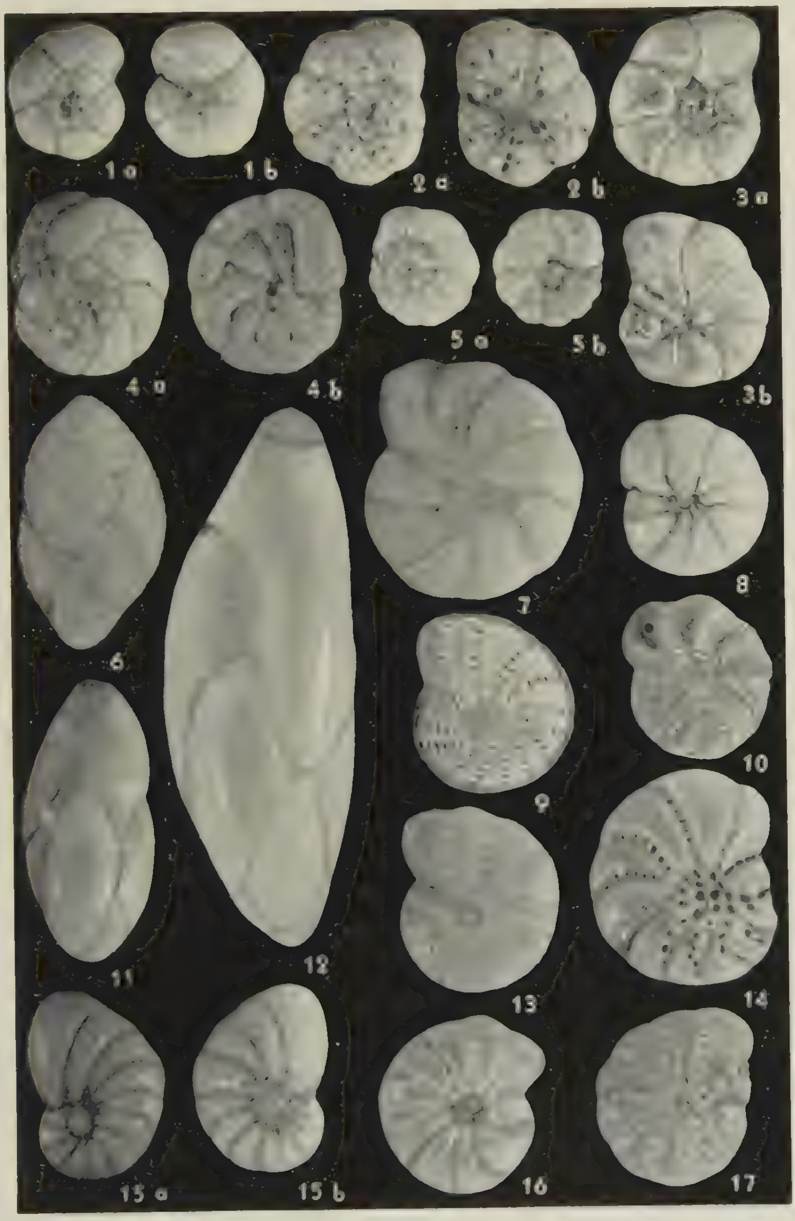
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PLATE 4

Figs. 1, 2. *Elphidium incertum* (Williamson) variants. X 50. Sta. 65.

Figs. 3, 4, 5, 6, 8. *Elphidium subarcticum* Cushman. (3–6) X 50. Sta. 105: (8) X 70. Sta. 29.

Figs. 7, 13. *Bulimina* aff. *aculeata* d'Orbigny. X 70. (7) Sta. 179; (13) Sta. 176.

Fig. 9. *Elphidium selseyensis* (Heron-Allen and Earland). X 50. Sta. 196.

Fig. 10. *Virgulina fusiformis* (Williamson). X 70. Sta. 194.

Fig. 11. *Bolivina pseudoplicata* Heron-Allen and Earland. X 70. Sta. 176.

Fig. 12. *Bolivina variabilis* (Williamson). X 70. Sta. 130.

Figs. 14, 15, 16. *Hopkinsina pacifica atlantica* Cushman. X 70. Sta. 194.

Figs. 17a, b, 18a, b, 19a, b, 20a, b. *Discorbis columbiensis* Cushman. X 50. (17, 20) Sta. 176; (18, 19) Sta. 114.

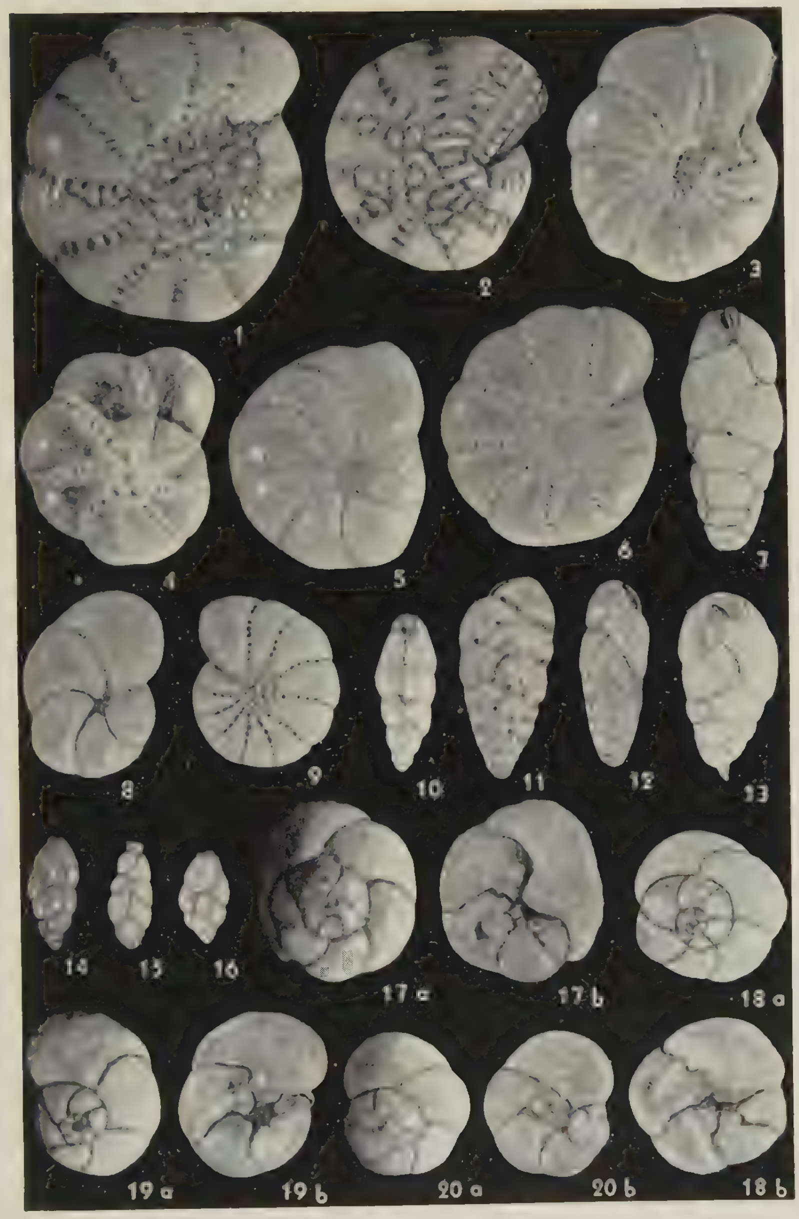
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PLATE 5

Figs. 1a, b. *Discorbis squamata* Parker. X 70. Sta. 126.

Figs. 2a, b. *Eponides frigidus* (Cushman). X 70. Sta. 145.

Figs. 3a, b. *Eponides frigidus* (Cushman) var. *calidus* Cushman and Cole. X 50. Sta. 100.

Figs. 4a, b. *Eponides wrightii* (H. B. Brady). X 50. Sta. 105.

Fig. 5a, b. *Rotalia beccarii* (Linné). X 50. Sta. 105.

Figs. 6a, b. *Poroeponides lateralis* (Terquem). X 50. Sta. 114.

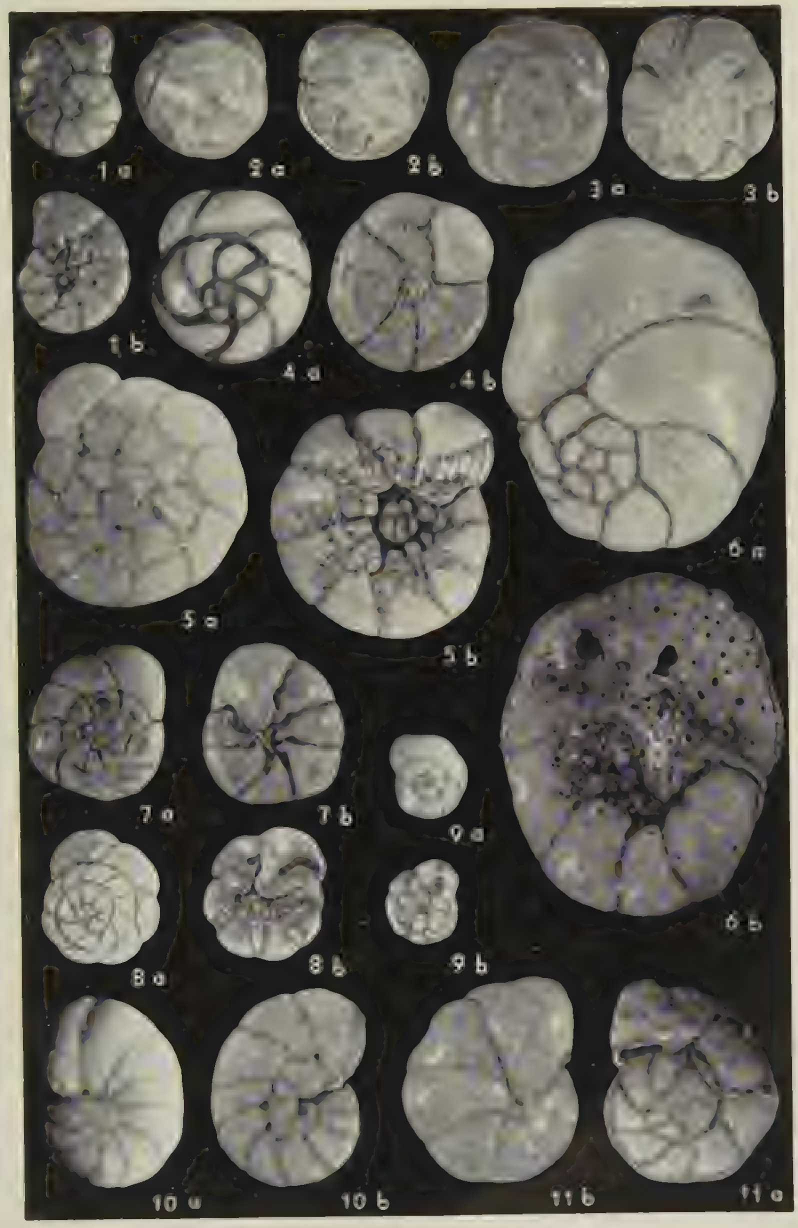
Figs. 7a, b. *Rotalia beccarii* (Linné) var. *sobrina* Shupack. X 50. Sta. 105.

Figs. 8a, b. *Rotalia beccarii* (Linné) var. *tepida* Cushman. X 50. Sta. 202.

Figs. 9a, b. *Pninaella* (?) *pulchella* Parker. X 82. Sta. 127.

Figs. 10a, b. *Cibicides concentricus* (Cushman). X 50. Sta. 180.

Figs. 11a, b. *Cibicides lobatulus* (Walker and Jacob). X 50. Sta. 176.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Contribution No. 594

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THE PROBLEM OF THE ICEBERG POPULATION IN BAFFIN BAY AND DAVIS STRAIT AND ADVANCE ESTIMATE OF THE BERG COUNT OFF NEWFOUNDLAND*

By I. I. SCHELL
(Woods Hole Oceanographic Institution)

THE iceberg population in Baffin Bay and Davis Strait is little known, yet it is intimately connected with the problem of the advance estimation of the berg count off Newfoundland and the safety of local and trans-Atlantic navigation in that general area.

A recent formula providing such an estimate at the end of March [1] is based primarily on the December–March pressure gradient† between Labrador (Belle Isle) and southernmost Greenland (Ivigtut) on a line perpendicular to the normal direction of the isobars over that general area. This pressure gradient may be presumed to reflect the intensity of the northerly winds in that region, and since the Labrador Current is partly wind driven, the pressure gradient may be said to reflect also to a certain extent, indirectly, the strength of the Labrador Current, both of which affect the drift of the icebergs.

An independent test of the formula using the data for the twenty-five year period 1926/7–1950/1 showed rather favorable agreement between the computed and actual deviations which, expressed in terms of the simple correlation coefficient, is $r=0{\cdot}81$.[1]

The significant measure of the unresolved discrepancy between the computed and actual deviations as shown by the value of the correlation coefficient substantially less than unity (above) is probably due to no provision in the formula for direct information on (1) speed, direction and temperature of the Labrador Current, (2) the iceberg population to the north from which the berg concentration off Newfoundland is recruited and (3) wastage of the bergs also by warm rains and winds.

To remedy the lack of information about the Labrador Current, a regular program of observations of the volume and temperature of the current was begun some years ago by the U.S. Coast Guard. The data obtained to date cover the eleven years 1928, 1931–6, 1938–41, 1948.[4] An analysis of the data through 1940[3] showed that few bergs tend to be accompanied by below average values of the current heat-transfer. Further, it appears that for the three years with the smallest volume of the Labrador Current—less than 3×10^6 m.^{3}/sec. (1931, 1940, 1941)) the count of bergs on the scale of 10 was 1·8, 0·1 and 0·1 respectively, and for the three years with the largest volume —$5{\cdot}0\times10^6$ m.^{3}/sec. or more (1928, 1933, 1934) the respective counts were: 5·6, 3·8, and 5·7 (Table I). The average volume of the current is $4{\cdot}0\times10^6$ m.^{3}/sec., based on the eleven years listed and the average value of the berg count, is 4·8 on the scale of 10. On the whole the observations are as yet too few for a more detailed comparison, but it would appear (Table I) that the changes in the current alone are not likely satisfactorily to account for all the variations in the berg count. It is worth noticing too that the values of the berg count computed with the aid of the meteorological formula referred to above are in about as good an agreement with the actual berg count as the results that may be deduced from the Labrador Current shown in Table I.

To obtain adequate information on the iceberg population north of Newfoundland, a census was first made by ship in 1940[2] and later repeated on a broader scale by airplane in 1948.[4] A census was also carried out in 1949 but none unfortunately in 1950. Indeed, censuses over a number of years in succession would probably be needed before their value in estimating in advance the severity of the iceberg season off Newfoundland could properly be assessed.

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* Contribution No. 594 from the Woods Hole Oceanographical Institution.

† Strictly speaking, pressure difference, as only with the average distribution are the two identical.

In addition to counting the number of icebergs in different sectors of Baffin Bay and Davis Strait, and deducing their movements from the presence of certain concentrations a year or two later, closer information about their actual drift once they break off the glaciers and leave the fjords is desirable. It is known that the bergs which come down off Newfoundland originate for the most part from the West Greenland glaciers with an insignificant number from the few small glaciers on the North American side of Baffin Bay. The general movement of the West Greenland bergs is northward, thence westward and southward. How far north the individual bergs will travel before turning westward will depend on the westward branching of the initially northward directed warm water of south-west Greenland and to a lesser extent on the winds in that general area. Conceivably, as the warm water off south-west Greenland begins branching off westward at a lower latitude, more bergs will cross to the west at these latitudes and the length of their journey will be decreased, but their melting rate will be increased by the less cold water.

TABLE I

Extreme values of Labrador Current and corresponding actual and computed severity of Iceberg season south of Newfoundland during 1928–1948 (n=11)

Year	*Volume*	*Iceberg count on the scale of 10*	
		Act.	*Comp.*
1931 ..	1·3 × 10^6 m.^{3}/sec.	1·8	3·0
1940 ..	2·8 ,,	0·1	2·1
1941 ..	2·3 ,,	0·1	3·3
1928 ..	5·1 ,,	5·6	5·1
1933 ..	7·6 ,,	3·8	4·7
1934 ..	5·0 ,,	5·7	6·2
Average all Observs.	4·0 ,, (1928–48 (n=11))	4·8 (1900–48 (n=49))	

To obtain a concrete picture of the behavior of the icebergs once they leave the west Greenland fjords, it is suggested that the bergs be marked. The most practical way to do this, it would seem, is to spray groups from different glaciers by color dust from the air in the hope that enough dust in solution or otherwise will stay with the berg even after occasional overturning. These bergs could then be searched for by airplane, and from their movements estimates made as to their course of travel, average speed and mortality. A successful tracking of the bergs in conjunction with wind data should provide also valuable information on the circulation of the waters in that area.

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Contribution No. 595

Särtryck ur Tellus nr 2, 1952

Recent Advances in the Study of Convective Clouds and their Interaction with the Environment[1]

By JOANNE STARR MALKUS
Woods Hole Oceanographic Institution and Illinois Institute of Technology

(Manuscript received 10 March 1952)

Abstract

Recent developments in two main phases of cumulus cloud studies are discussed; first the relations between the clouds and their energy sources in the subcloud layer and second, the interaction between the clouds and their environment in the cloud layer. Under the first heading, the various originating impulses for cumulus formation are mentioned, and how the character of this impulse affects the spacing, scale and temperature structure of the clouds. The possible origins of trade cumuli are considered. The second phase is primarily concerned with the nature of the resistive forces operating against cloud growth, how these arise and how they affect the clouds' life cycle. The resistive forces are shown to be of importance in the transports of momentum, moisture and heat by the cumuli and to serve as controls in the feeding of latent energy into the high tropical troposphere and hence into the general circulation.

I. Introduction

For the past five years or more, the cumulus cloud problem has been developing very rapidly. A summary of the recent contributions, involving an attempt to relate them to each other, shows not only that our knowledge of convective elements and their detailed structure is today far advanced beyond five years ago, but that what has been learned about convective processes is vitally connected to the most important meteorological problems, such as the vertical transports of heat, moisture, and momentum, the structure of the trade inversion, and even to the general circulation of the atmosphere.

Many of the key questions and ideas upon which the new important developments have rested were originally advanced by European or American meteorologists as far back as the 1930's. The critical observations by which to test the hypotheses and from which the orders of magnitude of the quantities appearing in the equations could be compared, however, were largely lacking until the large-scale observational programs undertaken by American agencies in the decade since the war. Outstanding among these programs were the Woods Hole Oceanographic Institution Caribbean Expedition (led by Wyman and Woodcock) in 1946, the United States Weather Bureau Thunderstorm Project (field studies 1946 and 1947), the University of Chicago Project Tyrena (Pacific Trade observations, 1947), the Hawaiian Pineapple Research Institute Field Study in 1948, and General Electric Company's Project Cirrus (flight programs beginning 1946). The contributions arriving as direct and indirect results of these field studies are still accumulating, and form the main material for this discussion. Nevertheless, the time is now approaching when many of the newly evolved questions raised by analysis of these data must await further measurements for their answers. One purpose of this summary will be to indicate the directions led by several of these questions and some possible observational approaches that they suggest.

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[1] Contribution No. 595 from the Woods Hole Oceanographic Institution.

For the purpose of critical evaluation, convection study may be broken down into three closely interwoven phases:

1. The detailed structure of thermals, cumulus, and thunderclouds; distribution in space and time of drafts, gusts, hydrometeors, entrainment, etc.
2. Thermals and convective clouds in relation to their energy sources.
3. Interaction of convective elements with their environment; their role in transport processes.

In the following discussion, results of the first phase will be introduced only as they contribute to the second and third phases of the problem. The physics of the condensation process, nuclei, state changes, and cloud electrification will be omitted since the present summary is almost entirely restricted to thermals and smaller cumulus in which icing does not occur. For these situations it is assumed that only the effects and not the details of the latent heat release need be considered.

II. Thermals and Convective Clouds in Relation to their Energy Sources

Because of the dominant role in the energy supply of cumulus played by condensation, and its regulation by the structure of the adjacent air, the major features of individual clouds may not differ widely, despite widely different initiating impulses. Nevertheless, the process which first raises parts of the air to saturation may significantly affect several features of the cloud layer as a whole, among them the spacing and scale of the clouds and often the sign and magnitude of the cloud-air temperature difference. This originating impulse may on some occasions be provided by organized thermal-convective circulations in originally unsaturated air, by unorganized thermal-convective bubbles, by occasional eddies in a well-mixed layer randomly hitting their condensation level, by wave motions within a layer or at an interface, or by updrafts caused by flow over barriers, convergence in the large-scale circulation patterns, sometimes due to fronts, seabreezes, or frictional differences, and possibly due to other effects not yet described. Many times, the effective impulse consists of a combination of several of these factors.

Lending itself most easily to theoretical analysis is the situation where the impulse for cloud formation lies in organized dry convection. So far, most of the analytical models attempting to describe the initiation of cumulus have had as their aim the prediction of the vertical motion field in unsaturated air. Two extreme physical models have been studied, namely, first, the motion field arising from uniform heating or cooling of an air layer at a horizontal boundary. This is the classical "convection cell" problem, first raised experimentally by Bénard (1900a; 1900b; 1901). The second model studies the convective motions resulting from localized differential heating. Despite the different physical situations, the underlying premises of all these approaches are similar. The basic hypothesis is that if convective updrafts are predicted in unsaturated, conditionally unstable air, and if sufficient moisture is present, cumulus clouds may be expected to form at the places of maximum lifting. The hydrodynamic equations of motion, continuity, state, and energy (either the heat conduction equation or the first law of thermodynamics) are set up and lead, usually by the method of perturbations, to a differential equation for the velocity and/or temperature field. In such a use of the hydrodynamic equations, an analysis strictly applicable only to laminar motion has been carried through and transformed by analogy to apply to the mean motions in a turbulent convective situation.

Bénard type convection cells and their relation to the cloud problem

The classical or Bénard-type convection cell theories have been well summarized in a review article by STOMMEL (1947a). The complexity of these perturbation equations is so great that only limited theoretical predictions are possible. The most famous is the criterion for the changeover from molecular conduction to laminar cellular convection first established by RAYLIEGH (1916). This criterion states that when the rate of temperature decrease with height (by analogy, potential temperature in the atmosphere) exceeds a critical value, steady polygonal cells should be observed. The critical temperature gradient depends directly upon the product of conductivity and viscosity and inversely upon the thermal expansion coefficient and fourth power of layer thickness. A preferred ratio between horizontal cell dimension and layer thickness is also derivable, giving cell diameters about 2.5—3.5 times their height. Controlled laboratory results (BÉNARD and AVSEC, 1938; SCHMIDT and SAUNDERS, 1938) appear to check these criteria in the case of laminar convection. They show steady, honeycomb-like, usually hexagonal cells which break down into rolls or strips as a horizontal flow is superposed. More recent experimental studies discussed by SEIDENTOPF (1941) and KUETTNER (1949) demonstrate that as temperature gradients are further increased to about 25 times the critical value (or, in practice, layer thickness increased by the fourth root of this factor, or about 2.2 times), a new change takes place in the flow and non-steady, growing and dying, convection cells occur. These cells have stronger and more localized updrafts, diameters approximately equal to their height, and a total lifetime given by the ratio of their height divided by the mean vertical velocity.

Intriguing though these results may appear, considerable caution must be exercised in applying them to the atmosphere and in seeking the origin of cumulus clouds in such cells. In the first place, uniform heating is assumed in the model and very rarely found in nature. Second, the models are based on constant conductivity and viscosity (laminar motion). Their large-scale analogies, the "eddy" viscosity and conductivity, even if they could be measured unambiguously, vary widely with space and time, and perhaps by orders of magnitude upon the onset of turbulent convective transport. This raises serious, though not necessarily insurmountable, difficulties before an observational attempt to determine whether the critical condition for the onset of Bénard-type convection cells is in real cases reached or exceeded. Therefore, in order to see if such models have any usefulness in application to the real atmosphere, it first must be ascertained whether regular polygonal or strip-like convective patterns are found. Some qualitative evidence has been presented (MAL, 1930; DURST, 1932; 1933; WALKER, 1933; BÉNARD and AVSEC, 1938; BRUNT, 1938). In the case of cumulus formation, Bénard-type cells should be sought only in the subcloud layer over the open sea, where the heating from below can be expected to be the most uniform, and where also the lapse rate is superadiabatic. Under these conditions, there exists some suggestive but not conclusive evidence. Among the most recent and pertinent is a brilliant observational paper by WOODCOCK (1940) deducing columnar and strip-like convective patterns over the autumnal Atlantic from the soaring routines of herring gulls. This study was followed by photographic investigations of the behavior of smoke trails over the sea off Massachusetts, Florida, and San Juan, Puerto Rico; the deflections in the smoke plumes were consistent with the existence of polygonal cells in the lowest hundred or so meters above the sea (WYMAN and WOODCOCK, 1947). The hope that similar polygonal patterns could be found in trade cumulus and that their roots lay in Bénard-type convection cells led to the now famous Wyman-Woodcock (Woods Hole Oceanographic Institution) expedition to the San Juan area in 1946. Disappointingly enough, not only were no polygonal or detectably regular cloud patterns found (see Fig. 1), but these observations showed that the existence of Bénard-type cells throughout any thick portion of the subcloud layer were almost certainly precluded, since the mean lapse rate in this area was slightly subadiabatic, becoming more stable as the cloud base level was approached (see BUNKER, HAURWITZ, MALKUS, STOMMEL, 1949) thereby shielding the cloud layer from such convective motions as might exist below. Thus the question of the origin of trade cumulus was left open and is still far from settled. Due to the great importance of the trade cumulus, and their role in the budgets of the air over the tropical oceans, this question

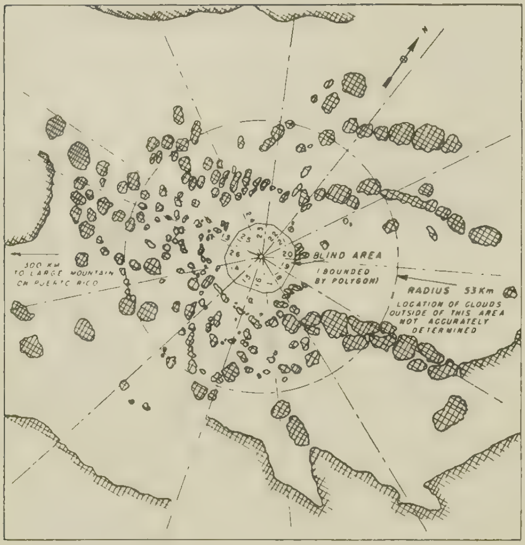
300 KM TO LARGE MOUNTAIN ON PUERTO RICO
BLIND AREA (BOUNDED BY POLYGON)
RADIUS 53Km
LOCATION OF CLOUDS OUTSIDE OF THIS AREA NOT ACCURATELY DETERMINED

Fig. 1. Map showing distribution of trade cumuli calculated from high altitude photographs Nos. 13—26 made by the Wyman-Woodcock Caribbean expedition on the afternoon of April 25, 1946. Scale: 1 cm = 10 km. Location of center 20°00′ N., 64°25′ W. The wind was east-southeast, decreasing slightly with elevation. Note the rather irregular spacing of cloudy and clear areas. Only the medium and large clouds within the 53-km circle have been accurately located. The shaded areas are distant cloud banks. See Figure 4 for one of the original photographs. After J. Wyman et al. (1946).

will be reconsidered in the concluding paragraphs of the present section. Meanwhile, attention will be turned to a model of cumulus origin in organized dry convection which has had rather definite observational verification.

A model of cumulus origin based on differential heating; cloud streets

Following the results of the Wyman-Woodcock Caribbean expedition, in which the problem of the origin of trade cumulus appeared rather obscure and complicated, the attention of the Woods Hole group became directed toward the broader question of the origin and roots of cumuli in general. It was then sought to determine whether any clear-cut cases occurred in which convective clouds could be related to a specific energy source and what role they played in the transports of heat and vapor from such a source to a passing air stream. The hope was to find a sample situation which could be studied both theoretically and observationally, and that the results of such a study in which only relatively few factors were operating on the airflow might eventually provide a starting point for the examination of more complex cases.

A rather striking example of patterned convective clouds with an identifiable "source" are the cloud "streets" formed by islands on sunny summer days. These periodically-spaced rows of small cumuli (see Figures 2 and 3) are frequently seen stretching far downwind of small, flat oceanic islands when slightly stable air flows across them.

The basic hypothesis underlying this study was that the heating by the island excites one or more of the "free periods" of the unsaturated stable airstream, creating a wave-like pattern in the stream lines downstream of the "obstacle" and that condensation may sometimes occur at the wave crests. If the air is also conditionally unstable, these may be preferential spots for the outbreak of cumuli, and the wavelength of the oscillations may then be inferred from the cloud spacing. A theoretical analysis (Malkus and Stern, 1951) was undertaken, similar in principle to those on convection cells, but in which following Langwell (1951a) and others, the first law of thermodynamics was the energy equation. Thus a distribution of heating as a function of space could be assumed, so that the air would be heated over the island and not elsewhere. From this, it is predicted that the production or non-production of lee waves (visible as cloud streets if sufficient moisture is present) does not depend, within wide limits, upon the character or space distribution of the heat source, but upon the properties of the air stream before it reaches the island. Specifically, no significant downstream oscillations are expected unless the atmosphere possesses some non-uniformity in the vertical, such as a change in wind speed or a very strong inversion. Second, the wavelengths of the lee waves, when they do occur, depend only upon the undisturbed stability, windspeed, and height of the discontinuity and are independent of the exact form of the heating. For islands about 10 km wide under normal insolation, the amplitude of the vertical motions in unsaturated air depends directly on the heating, inversely on the square of the windspeed and may exceed $^1/_2$ m/sec.

An observational program carried on by **Malkus** and **Bunker** (1952) showed that in cases where the island cloud streets were observed, a wind change at some upper level was found. The spacing checked the predicted wavelength in every instance (see Fig. 2 and 3). In addition to verifying the major premises of the simple theory, these observations suggested several improvements and new lines of inquiry, leading to the removal of the assumption of arbitrarily distributed heat sources and the inclusion of the effects of turbulent eddying and a well-mixed ground layer. Even without the refinements, however, this investigation has demonstrated that in some instances convective clouds do have their origin in unsaturated thermal-convective motions, and that perturbation methods predicting these motions have been successful in predicting the occurrence and scale of the clouds..

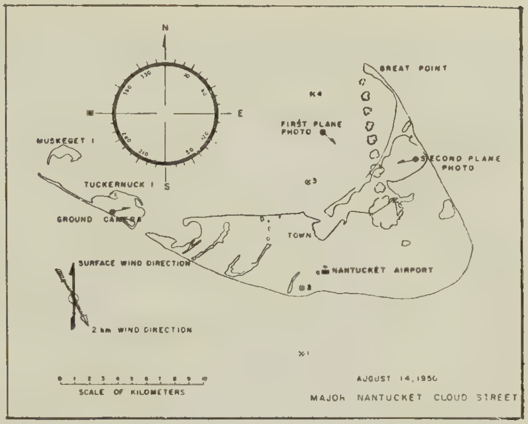

Fig. 3. Scale map of cloud street shown in Fig. 2. The numbered crosses indicate the positions at which airplane soundings were made. After **Malkus** and **Bunker** (1952).

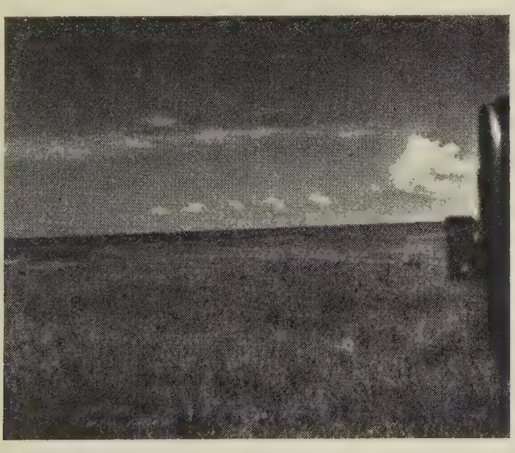

Fig. 2. Typical cloud street formed over and to the lee of Nantucket Island, Aug. 14, 1950. The low-level wind blows from right to left. The first three clouds from the right were over the island; those remaining were over the downwind waters. The spacing of the clouds was measured as 1 km, within experimental error of the predicted wavelength of lee waves. After **Malkus** and **Bunker** (1952).

Other cases of cloud streets have been observed which may have a similar origin, such as those formed by the flatter portions of the Hawaiian Islands.[1] In the lake country of the far north, especially on the Scandinavian peninsula, a common sight is 50—100 km long rolls of cumuli extending parallel to the wind. These have been described by **Kuettner** (1949). Since they appear mainly on sunny days following cold fronts, it is quite likely that their origin also lies in differential heating, although wind shear and the earth's rotation must play an important role in their maintenance.

Certain common features, however, may be sought in all cumuli whose individual origin thus lies in any organized dry-convective updrafts and these may provide a way to recognize this class of clouds from preliminary observations. First, they will usually form in recognizable patterns more or less simultaneously; second, such clouds will possess "roots" or detectable updrafts of cloud scale extending well below their bases and through a large fraction of the subcloud layer; and third, like several other categories of cumuli, they may at times be colder than their surroundings (discussed by **Bleeker** and **Andre**, 1950) if the initial updrafts are sufficiently strong.

Cumuli formed in lines or areas of convergence

Frequently over heated peninsulas or islands, of cumulus clouds appear which can definitely be associated with a "seabreeze front". These have been studied in Hawaii by **Leopold** (1949) and over Cape Cod, a peninsula on the eastern

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[1] Described to the writer by Mr. Wendell A. Mordy of the Hawaiian Pineapple Research Institute.

United States seaboard, by MALKUS, BUNKER, and MCCASLAND (1951). These seabreeze clouds owe their existence only indirectly to heating, which may not be strong enough to release the conditional instability except upon the addition of a sharp line of convergence at the zone where the seabreeze meets the gradient wind or the opposite seabreeze. Whether the updrafts caused by the clash of these two wind systems serve merely as a trigger to release self-sustaining convective clouds with warmer temperatures than their surroundings, or whether the initial upward velocity is sufficient to maintain clouds which consume energy and may thereby be colder than their surroundings probably varies from instance to instance. In any case, the individual clouds would not be expected to show deep roots. This expectation was supported by the Cape Cod study, in which the seabreeze cumuli were noticeably warmer than their environment at all levels.

Another way in which convergence extended over wider areas may serve to trigger the outbreak of cumuli is by vertical stretching of the so-called "mixed" or ground layer. If the top of the mixed layer over a wide peninsula, for example, lay somewhat below the condensation level and then a seabreeze circulation or convergent flow of other origin were superposed, so that in places the top of the mixed layer approached or reached the condensation level of the air parcels within it, random eddying would, under suitable conditions of instability, cause clusters of cumuli to break out in these places. Such spreadout, gradual convergence probably plays a significant role in the onset of convective cloudiness over the Cape Cod and Florida peninsulas (see BYERS and RODEBUSH, 1948; BYERS and BRAHAM, 1949) even when no sharp "seabreeze front" is present, and convergent flow (perhaps of other origin) probably remains as the most plausible explanation of the cluster-like formations of trade cumuli, as shall be suggested presently. Clouds triggered in this manner clearly will not show roots in the sense this term has been defined in the preceding discussion, although warm, moist pockets may be detectable in the subcloud layer prior to their appearance.

Probably the most important effect exerted by convergence on convective clouds, however, lies not just in triggering their outbreak, but in determining to a large extent how far they will develop once condensation has occurred. The role of convergence in the interaction of clouds and environment is discussed in the concluding paragraphs of this paper.

On the possible origins of trade cumuli

The trade cumuli are one of the most dramatic and vital features of the subtropical atmosphere (see RIEHL, 1950). Day and night they grow and decay over a hundred million square kilometers of warm oceans, their bases at the small stable stratum topping the mixed surface layer (~ 600 m), their tops pushing against, and some of them penetrating, the trade inversion (base averages 2 000 m). Their degree of development, ranging from scattered cumulus humilis to large cumulonimbus, is controlled by the height of this inversion, which in turn is regulated by the divergence field of the passing synoptic systems. In relatively undisturbed weather, they have the characteristic appearance shown in Fig. 4, and form in clusters separated by about 30-km wide clear areas, as shown in Fig. 1. As these cloud columns rise, eventually mixing partially with the inversion air aloft, they carry with them vast amounts of energy in the form of latent heat, raised initially from evaporation at the sea surface. It was shown by RIEHL, YEH, MALKUS, and LASEUR (1951) that the net heat and vapor transported upward by these cumuli is easily sufficient to account for the wellknown downstream rise in height of the trade inversion, which goes on in the face of overall subsidence and divergence. Therefore, the relation between these clouds and their moisture and energy sources in the subcloud region warrants study.

Evidence on these points is still extremely scarce, and at first glance, perhaps even contradictory. However, for one particular locality, namely the Caribbean near San Juan, in one relatively undisturbed April period, certain deductions may be safely drawn. First, these individual clouds did not have roots. This is not surprising in view of the preceding discussion (page 75) which showed that even if thermals or convection cells were found at low levels above the sea (at ship's deck level, for example), the stabilization of the air as

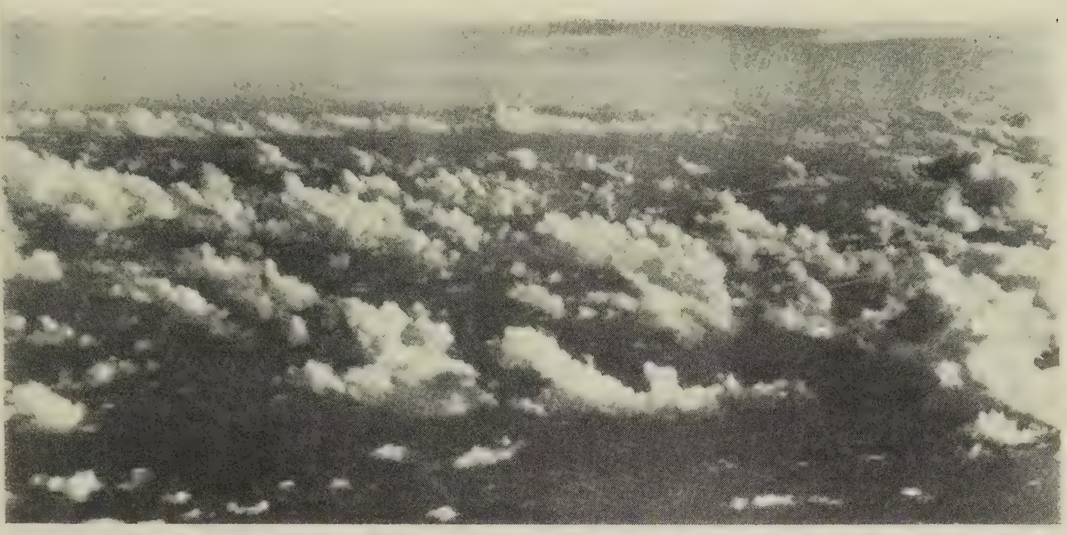

Fig. 4. High altitude photograph No. 15 of trade cumulus made by the Wyman-Woodcock expedition on April 25, 1946. One of the series of photographs used to construct Fig. 1. The camera was pointed outward from the center along line 15 in Fig. 1, so that the photograph gives a cross-section exactly in the plane of the east-southeast wind. The wind therefore blows from left to right across the photograph and decreases with height. After WYMAN et AL. (1946).

cloud base is approached would damp them out long before saturation. Furthermore, BUNKER et AL. (1949) showed that the major features of the subcloud layer, with maximum turbulence at 300 m, decreasing to a minimum at cloud base, were incompatible with the deep penetration of convective updrafts. Supporting evidence was found in horizontal accelerometer runs flown below cloud base, in which no increased turbulence appeared under the clouds.

A second significant feature of the trade cumulus studied by the Wyman-Woodcock expedition was their buoyancy. The in-cloud temperatures were, on the average, warmer than those of the environment, wavering between a + 1° C excess and a — 2° C deficiency near the cloud tops. The buoyancy forces were calculated in two cases by STOMMEL (1951) and in each case were positive through the lower portion of the cloud, becoming negative in the top few hundred meters, indicating overshooting. It seems likely that during a major fraction of their life cycles, these clouds were self-driving and not running on the energy provided by an external impulse.

For these two reasons, it is not reasonable to seek the origin of these clouds either in dry thermals of cloud size or in very sharp convergence lines in the flow, but most plausibly in gradual variations in the depth of the mixed surface layer. On the average, the top of the mixed layer was found to be at about 85 % the height of the lifting condensation level of the lowest air. Variations of several hundred meters from day to day and even within a few hours on the same day were noted. On some occasions its top reached or exceeded the condensation level, and it was, in the mean, noticeably higher in cloudy than in clear areas. One or more mechanisms, then, causing spatial oscillations in the thickness of the mixed layer are needed. These are probably of the dimensions of the cloud clusters, random eddying in these regions accounting for the outbreak of individual clouds. It is readily shown that fluctuations in the thickness of the mixed layer are only very weakly coupled with variations in the height of the trade inversion and the depth of the moist layer as a whole. Attention must therefore be directed to independent, weakly convergent flows set up within the subcloud layer itself. LANGWELL (1951b) has proposed unstable gravitational waves at the interface between the nearly adiabatic ground layer and the isothermal stratum at its top. One should also inquire about more random causes such as slight inhomogeneities in sea surface roughness, radiative properties, or temperatures on a 10—30 km scale.

The deductions just made should not be generalized without more observations to apply to the origin of trade cumuli in all cases. In several examples of Pacific clouds, **Barrett** and **Riehl** (1948) have presented evidence which may indicicate negative buoyancy throughout a cloud. To be sure, their examples were cumulonimbus, indicating strong convergence in the large-scale flow. Under such circumstances it is conceivable that an initial updraft might provide enough kinetic energy to build a cloud against both friction and slight stability. The orders of magnitude cannot be estimated accurately until more is known of the resistive forces on clouds. In conclusion, the evidence gathered so far by no means precludes the possibility that the origin of trade cumuli may be quite different over different parts of the subtropical oceans or even over the same region at different times. This suggestion is supported in the next section when resistive forces on clouds are discussed.

III. The Interaction of Convective Elements with their Environment

The preceding section has dealt with the relation between the clouds and the subcloud layer. Various mechanisms were discussed for raising heat and moisture through this layer so that they are available for cumulus formation. How these properties are further transported within and through the cloud layer depends upon the dynamics of the individual clouds, and particularly upon the interaction of the cloud with its environment.

This approach to the cloud problem as part of many larger ones was relatively new with the Wyman-Woodcock expedition and was phrased clearly in the first written report of this group (**Wyman** and **Collaborators**, 1946). In the classical development of meterology, cumulus clouds were regarded almost entirely as "weather phenomena", to be predicted as part of the synoptic situation. The main interest was, therefore, in "stability criteria" and the early work on convection consisted primarily of the evolution of thermodynamic methods to predict the onset and probable degree of development of the clouds. Their internal structure was regarded as interesting mainly as it led to precipitation or affected aviation. The interaction of the ascending parcel or column with its environment was ignored.

Dissatisfaction with these results soon appeared, however, when it was frequently found that cumuli failed to grow tall even when the parcel method stated that a vast amount of energy was available to them. Papers by several prewar writers pointed to the inhibitory effects exerted by the environment, in particular a brilliant paper by **Namias** (1939), who described the cutting off of tall cumulus towers by mixing. **Christians** (1935) and other European authors set up a theoretical framework for discussion of the several resistance forces operating against the growth of cumulus clouds, but at that time there were not adequate data even to estimate correctly their orders of magnitude, and hence their possible importance in a cloud's life cycle. Observations leading to the quantitative calculation of one of these resistance effects were for the first time provided in 1946 by the Wyman-Woodcock expedition to the trades.

This expedition found that temperature lapse rates inside clouds were, contrary to classical expectations, not moist adiabatic but considerably steeper, and that the in-cloud temperatures fluctuated with height, as if some sort of turbulent mixing process were taking place. At this point, **Stommel** (1947b) introduced, by analogy with the simple fluid jet, the idea that environment air was continuously "entrained" and mixed with the rising cloud air. From comparison of temperatures and mixing ratios inside and outside the cloud, he devised a method to determine the fractional amount of the entrainment, level by level. In the tradewind clouds studied, it frequently corresponded to a doubling of the mass flux of the rising air in 1 km ascent.

While the purpose of the entrainment paper by Stommel was specifically to explain the departure from a moist adiabatic lapse rate inside trade cumulus, it provided the cornerstone for many contributions to follow. From consideration of the effect exerted by the surrounding air upon a cloud and its logical converse, the effect exerted by the cloud upon the surrounding air, a framework can be set up to investigate many previously baffling problems. For example, it can now be understood why observations sometimes showed cloud tops which ceased growing while warmer than the environment, and why "pulsating" cumulus towers are rare. A suggestion can be made concerning the different features observed in trade cumuli contrasted with their middle-latitude counterparts. The effects of windshear upon convection can be discussed analytically, leading to at least preliminary models of convective clouds as transport elements. In effect, the role of cumuli, especially of trade cumuli, as an integral part of the layer in which they grow, rather than as incidental photogenic objects sometimes acting up to produce aircraft hazards and rainfall, is now a fruitful topic of investigation. Clearly, the question of predicting the onset and growth of these clouds from initial air conditions becomes considerably more complex as a result of entrainment and other resistive effects.

Stability criteria and their modifications by resistive forces

The model of the air parcel which rises without interaction with its environment, while now regarded as a drastically oversimplified one to describe real cases of convection, still serves an important function as a clearcut limiting case, just as the undamped harmonic oscillator is a clearcut limiting case in studying the behavior of real, frictionally damped oscillators. The original purpose in setting up stability criteria was to establish the conditions of thermal stratification in the environment under which an air parcel when displaced slightly from its equilibrium position would acquire an initial acceleration away from its origin. Since a rising, saturated, non-interacting air parcel would cool at the moist adiabatic lapse rate, the well-known result was obtained that if the environment cooled more rapidly with height than this rate, the ascending parcel would become less dense than its surroundings and would accelerate upward.

Strictly speaking, these criteria regarding initial accelerations stand unmodified, since frictional and resistive forces come into action only after an initial velocity has been acquired. The difficulty arises in attempting to apply them to finite convective motions. The first quantitative recognition that buoyancy forces were cut down by the parcel's environment came with the slice method of J. BJERKNES (1938). He recognized that the compensatory sinking (usually dry adiabatic) of the outside air would cause its warming, thus cutting down the relative temperature excess of the rising parcel and thereby its buoyancy. This effect was shown to be greater the more a region was filled with updrafts because of the requirement thereby of more limited, hence stronger downdrafts and consequent intensified warming of the sinking air.

The entrainment of drier environment air, however, ordinarily reduces buoyancy forces far more than does compensatory sinking. Simple calculations show that even under exaggerated conditions of 3/10 of the area occupied by active updrafts, the effects of compensatory sinking reduce the buoyant energy predicted by the parcel method only by about 40 %. Upon entrainment of a normally observed fraction of outside air with relative humidity about 70 %, the buoyant energy may be reduced by over 90 % from that predicted by parcel considerations.

AUSTIN (1948) has discussed in detail the reduction in buoyant energy under various assumed rates of entrainment and environment humidities. He showed what the lapse rates inside clouds would become, and hence what environment lapse rates would be necessary for cloud growth, thus illuminating the inhibitory effects of a dry environment upon the development of large cumuli. Such methods, however, can only be expected to give statistical probabilities for cloud growth, rather than clearcut predictions from an initial stratification. The reason is that one or more assumptions, usually including that of an average entrainment rate, is required. Actually, the entrainment rate which will prevail at a given time, under given conditions is itself a complex, adjusting function of the vertical motions, cloud size and other factors, and may be highly variable. Hence it is probably no longer fruitful to discuss convection from the point of view of onset criteria, parcels, and initial perturbations, except for reference, as is the undamped harmonic oscillator in physics. The more difficult problem of a cloud's "life cycle" and the interacting adjustments between buoyancy and resistance after the updrafts are of finite size must sooner or later be tackled.

Present knowledge of the resistive effects on cumulus clouds

It has been shown that the buoyancy forces producing cloud growth are reduced by two causes: first, by the compensatory sinking of the environment; and second and more drastically by the entrainment of drier outside air. Clearly, if the buoyancy forces on its air are upward, the cloud grows, and hence for stability criteria, the net buoyancy is all that need be determined. Nevertheless, these two effects, compensatory sinking and entrainment, further reduce the kinetic energy in an existing updraft via ordinary friction or reduction of the draft's upward momentum. Therefore, these too must be considered in a "life cycle" approach, since anything reducing the vertical motions in turn acts back to reduce the resistive effects, which control the buoyant energy release, and so forth. The nature of these "drag" forces has been set forth in an excellent treatise by Schmidt (1947) who shows that they are exactly the same forces which would oppose the motion of a non-buoyant jet of water created within a resting fluid. The first he calls "form" or "profile drag", and the second "skin friction", similar to terminology in aerodynamics. The form drag is due to the pushing aside of the surrounding medium as the jet grows and accelerates it back as a "countercurrent". The skin friction arises from viscous forces at the moving boundary, which in the fluid jet give rise to entrainment. In contrast to aerodynamics, however, in which solid bodies are moved through fluids, the form or profile drag may prove to be neglectable in many aspects of the cloud problem. Clearly, it will be most important as the cloud tower grows rapidly upward and the countercurrent is being established, and less so when the cloud later approaches a steady state. Entrainment and its consequent reduction of upward velocity, however, is clearly operative throughout the entire life of the updraft. This conclusion concerning relative drag magnitudes may be invalid, though, in the later considerations of the horizontal motion of the updraft through the air, since a horizontal countercurrent must then continually be produced similar to the case of moving solid, thus creating a pressure differenc in the horizontal across the draft.

For preliminary models of a cloud's growt and life cycle, it would indeed be fortunat were both resistive effects due to countercurrents neglectable compared to those due t entrainment. In view of the above discussio it seems plausible to proceed upon this tentativ assumption, especially since both buoyanc reduction and momentum reduction by entrainment can be readily dealt with analytically The buoyancy reduction by countercurrent was shown to be relatively smaller, and thei frictional effects seem prohibitively comple at present. Intensive observational tests of suc models will then be called for, to determin whether this assumption requires later modification.

Preparatory to any analytic treatment of th interaction of entrainment and buoyancy i cloud dynamics, however, a further discussion of the entrainment mechanism is required. Tw points of view prevail at present concernin this topic. It is this writer's belief that thes points of view are by no means incompatible but rather arise from two different operationa definitions of entrainment. Stommel (1947b calculated the proportion of environment ai of known properties which must have mixe with the rising air to produce the observed in-cloud distribution of temperature and moisture By his analogy with the spreading jet in flui mechanics he implicitly assumed that all thi mixed air was dragged along with the updraft permitting its cross section to expand wit height. Other writers (Austin, 1948; Houghton and Cramer, 1951) have assumed explicitly that the draft cross section remain nearly constant with height, in more apparen agreement with existing sparse observations The latter writers contend that the majo entrainment is that which is required t preserve continuity in a constant cross-sectiona cloud whose ascent rate increases upward The observed entrainment rates called upo by them are based upon direct measuremen of inflow winds around clouds, such as th calculations described by Byers and Braha (1949) and are much smaller than those foun by Stommel. Clearly, there is no conflic between these two viewpoints if the possibilit is admitted that all the air which is in or becomes mixed with that ascending is not retained indefinitely within the updraft, but that some is "detrained" during the ascent.

Stommel's calculations might be said to give the "gross entrainment" or the total amount of environment air mixed with cloud air, while the Austin, Houghton-Cramer method considers "net" or as they call it "dynamic" entrainment, the difference between the two amounts in a given cloud being detrained. An observational test of this hypothesis would be provided if a vertical velocity profile of the cloud were measured simultaneously with in-cloud and environment soundings. The amount of net influx required to preserve continuity could then be calculated and compared to the total amount of outside air mixed with cloud air. Although such measurements are still wanting, some less direct evidence supporting this hypothesis appears in the following sections.

Recent approaches to cloud dynamics

HOUGHTON and CRAMER (1951) have constructed the first completely analytic model of the interaction of buoyancy, vertical motions, and entrainment in a cloud. Although their work, because of the assumptions necessitated by present data, cannot yet be regarded as a "life cycle" model, it nevertheless represents a significant step in this direction.

Under the basic assumption that dynamic entrainment be the only resistive effect, these authors obtained and solved differential equations for the height distribution of vertical motions, net mass influx, and liquid water. These equations were derived from the laws of mass, momentum and energy conservation under the additional restriction to a steady-state cloud of constant cross section. Their work has the great advantage over previous attempts in that the entrainment rate need not be assumed or inferred but appears as one of the dependent variables in the system of equations and hence can be predicted. The vertical velocities so calculated are of the observed order of magnitude, but probably somewhat too great. Their derived influx rates are comparable to but larger than those found by the Thunderstorm Project (BYERS and BRAHAM, 1949) and smaller than most of those found by STOMMEL (1947b). They found that although the liquid water content of their clouds was considerably less than that predicted by the parcel method, dynamic entrainment of even very dry outside air does not suffice totally to "dry out" the cloud. This appears to be in conflict with many observations (MALKUS, 1952). Clearly, then, the greatest departure from realism of such a model is that it fails to provide a way in which updrafts may die out with height, other than by increasing stabilization of the environment. Dynamic entrainment ceases to operate as a resistance when the ascent rate has stopped increasing upward, since no more influx is then required to maintain continuity. The authors, however, themselves suggested that additional resistances, such as form or profile drag, weight of liquid water, or further mixing with the environment probably should be introduced.

A second entrainment paper by STOMMEL (1951) appearing simultaneously with that of Houghton and Cramer provides interesting comparison with their work. He computed, again using the Wyman-Woodcock soundings, the vertical velocity distribution within these trade cumuli. Similar to Houghton and Cramer, he assumed a steady state and that the only resistive effect was the entrainment inferred from observed soundings. The vertical velocities obtained were comparable to those of Houghton and Cramer, although the environment air of the tradewind clouds was far moister. Some more striking differences also appeared. Although Stommel's rate of increase of updraft with height was nearly the same as that predicted by Houghton and Cramer, the measured "gross entrainment" was far greater than that needed to satisfy continuity and continued at a high rate above that level where the vertical motions began to diminish upward.

If further observational work corroborates these indications, a mechanism to cause such additional entrainment or mixing must be sought. A factor not included in the Houghton-Cramer model which operates in real situations is shear in the external wind. Observations of clouds in the Woods Hole (eastern U. S.) area seem to indicate that those clouds which cease to grow despite warmer temperatures at their tops occur on days of pronounced wind shear. The Thunderstorm Project (BYERS and BRA-

HAM, 1949) also found that strong shear exerted an inhibitory effect upon thunderstorm development.

Some effects of windshear upon convection

The crux of these investigations is that momentum is a vector quantity. While the preceding discussion has shown that the vertical momentum relations in a cumulus cloud are extremely complex, due to the interaction of buoyancy and friction, the horizontal component is altered by friction alone. If a parcel or updraft (the presence of liquid water is, for the moment, unimportant) were to rise without interaction through an environment in which the external wind changes with height, it would acquire a velocity relative to the air, since its forward momentum would remain that of its original level. If the shear vector between any two levels is defined as the upper minus the lower wind, the parcel's relative velocity would be in the sense opposite to this.

It has been shown by MALKUS (1949a; 1952) that frictional forces act to reduce but do not eliminate this relative velocity. A striking verification of this prediction was found near Woods Hole, when on several days of marked wind turning with height, small cumulus were actually observed moving at an angle of 45° to the wind at their midlevel. This case has been discussed quantitatively by MALKUS, BUNKER and MCCASLAND (1949).

The entrainment of outside air is one factor operating to alter the momentum of the updraft toward that of its surroundings. The total amount of outside air mixed with the updraft must be included, hence the gross entrainment rates found by STOMMEL (1947b) were used in these considerations. When this is assumed to be the only resistive force, relative horizontal velocities of about 2 m/sec should be common about 1 km above draft base, for normal wind shears. If form or pressure drag creates additional resistance of equal magnitude, the relative velocities are decreased about 40 %. Direct verification of relative cloud-air velocities was found in the Thunderstorm Project's tracking of clouds by radar (see BYERS and BRAHAM, 1949). At roughly 1 km above cloud base, they found average relative speeds of 2 m/sec, increasing to an average of 5 m/sec at 6 km (fairly large average windshears).

The relative velocity between draft and environment has been shown by MALKUS (1949a) to produce important asymmetries between the location of updrafts and that of the visible, liquid cloud. How these may arise is easy to see. If the horizontal speed of the draft through the air is of the order of 1 m/sec, it will be greater than the normal rate of inflow of entrained air, which for a stationary draft might be fairly symmetrical around the periphery. Hence by vector addition, the inflow rate on the relative upwind side is greatly increased and actual outflow or detrainment of cloudy air from the updraft may take place on the opposite side. If verifiable observationally, a mechanism has clearly been presented whereby the total influx or "gross entrainment" is caused to be greater than the dynamic or "net entrainment" required to preserve continuity.

Several types of observation verify this prediction. The most striking are time-lapse motion pictures (motion pictures exposed at long intervals, say one every five seconds and projected at normal speed of 16 per second). A number of sequences made in the Woods Hole area showed cloud fragments streaming out from one side of the moving cumuli, becoming caught in the adjacent downdraft and dissipating, while the cloud grew vigorously and put out new towers on the opposite side. In each case, the cloud dissipated on the downwind side of the shear vector and grew on the upwind side (see discussion by MALKUS, 1949b; 1952). Nineteen sequences of films made by the Thunderstorm Project in Florida were also checked and the prediction verified in every case that the windshear for the region could be determined reliably (17 cases). In Fig. 4, showing trade cumulus, the wind blows from left to right across the photograph and decreases upward so that the shear vector points toward the left. Signs of active growth, new turrets, and turbulence are apparent on the right edges of the clouds, while they appear fuzzy and weak on the left edges.

An additional verification of these asymmetries in trade cumulus was found from the accelerometer records made in the horizontal airplane traverses by the Wyman-Woodcock expedition. Fig. 5 presents an average of eight such horizontal traverses through trade cumuli, in each of which the ambient wind increased upward. If it can be assumed that active updrafts are associated with cloud-scale turbulence the data are easily interpretable as follows: In the region δ, where cloud air has been blown off the updraft, the water droplets may be expected to evaporate and the cloud die. In the region D, where air is being brought into the updraft, new cloud may be expected to form. Similar observations were reproduced by MALKUS, BUNKER and MCCASLAND (1949) in the Woods Hole area. Thus it is seen that a cumulus is not simply an aggregate of droplets, drifting passively with the wind, but rather is a transient, dynamic balance between rapid growth and equally rapid destruction. The air is seen to have a component of motion *through* the updraft. An extreme case of air motion through a draft is found in clouds which appear to remain standing near mountain tops for hours despite strong winds.

The asymmetrical distribution of upward accelerations within thunderclouds and its relation to windshear has been discussed analytically by LANGWELL (1951c). She showed that a large cumulus is most likely to begin transition to a mature stage on its edge toward which the shear vector points (δ region), because there the updrafts are weakest or absent and yet liquid particles plentiful enough to cause a significant downward drag. Her predictions concerning the side of convective clouds that first produces rain were well verified from data taken by the Thunderstorm Project. The downward transport of momentum by the downdraft obeys principles similar to those just presented and is discussed by BYERS and BRAHAM (1949). The role of this downward transport of usually very high westerly momentum has been shown to be important in the cold air outflow from thunderstorms, the initiation of new thunderstorm cells, and the formation and movement of squall lines.

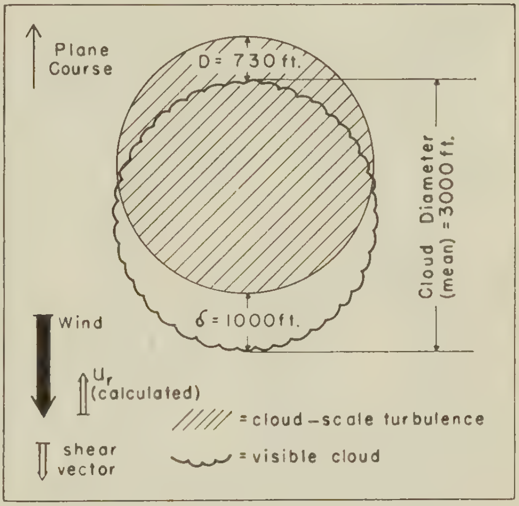

Fig. 5. Average of eight horizontal airplane traverses with accelerometer through middle levels of trade cumuli. Traverses were made by the Wyman-Woodcock Caribbean expedition, April 1946. In each of these cases, the wind increased with height about 1 mps/km. The cloud-scale turbulence was at least an order of magnitude in excess of clear-scale turbulence. The time of entrance and exit into visible cloud was recorded directly on the accelerometer record. The arrow labelled U_r is the cloud motion seen by an observer moving with the wind; an observer riding on the cloud would feel a wind in the opposite direction. After MALKUS (1949a).

The slopes of cumuli; trade cumuli vs. those of middle latitudes

The slope of an updraft at any level depends only upon the ratio of the vertical speed to the departure of the horizontal speed at that level from that at its base. Therefore, it is very easy to calculate the slopes of the clouds discussed in Stommel's second entrainment paper (1951). The horizontal speed of the clouds can be calculated from the entrainment rate and observed wind shear using the technique evolved by MALKUS (1949a). Stommel already calculated the vertical speeds. The result of this calculation is reproduced in Fig. 6. This should be compared with the photograph presented earlier, in Fig. 4, which was made in the same area at the same time as the sounding used by Stommel. Due to negative shear (easterlies decreasing upward), the predicted slope of the cloud is upwind, as is the observed slope. Most of the clouds in the photograph appear to slope more strongly backward than does the theoretical cloud. This cannot be due to the 18 000 ft altitude from which the photograph was taken, since even the nearest clouds were about 70 000 ft from the camera. It may be due to additional resistive forces such as form drag, not included in the theory, or it may be that most of the clouds pictured here were in a later stage of their life cycles than Stommel's, thus having

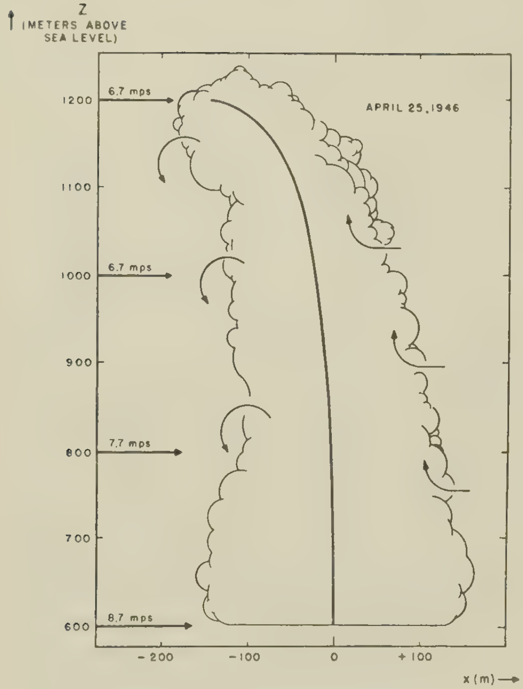

Fig. 6. Theoretical slope of the trade cumulus on April 25, 1946 whose vertical velocity profile was calculated by STOMMEL (1951). The dark arrows to the left are the observed external wind. The light curved arrows represent schematically the predicted air motions into and out of the cloud, according to MALKUS (1949b). The cloud should be building on the right and decaying on the left side as it moves from left to right more rapidly than the external wind. Compare with Fig. 4.

slower ascent speeds. A more detailed study of cloud slopes (MALKUS, 1952) shows that greater horizontal friction forces or weaker updrafts produce more slant, as does stronger external shear, other conditions remaining the same.

The inhibitory effect of a strong slant upon cloud growth has been discussed by BYERS and BRAHAM (1949). They demonstrated that a cloud grows by the production of successive turrets at or near its top. If wind shear is weak the new turrets grow in air already moistened by dissipated predecessors. If external shear is strong, the old turrets become strongly slanting as their updrafts decay. The new turrets with strong drafts grow nearly vertically and hence are penetrating drier air. That small cumuli as well as thunderclouds grow in this manner has been verified by time-lapse movies in the Woods Hole area where individual towers have been observed to have life spans lasting from six to sixteen minutes.

An additional inhibitory effect of wind shear upon cloud growth has been suggested in the foregoing discussions. The relative cloud-air horizontal velocity increases linearly with wind shear. If it can be shown, as proposed here, that additional entrainment results from this motion of the cloud through the air, then the resistive effects and buoyancy reduction are substantially augmented by wind shear. A suggestion concerning the difference between trade cumulus and their extra-tropical counterparts may now be feasible.

The constancy of the trade wind through the subtropical cloud layer is well known. The average shear vector through a corresponding layer in the Woods Hole area, for example, was 2—3 times greater (6 mps/km) in the summer months than near San Juan during the Wyman-Woodcock expedition (2—3 mps/km). From the data of RIEHL et AL. (1951), the shear in the Pacific Trade appears to be even smaller (~ 1 mps/km). Trade cumuli may therefore be operating against considerably smaller resistive forces than middle latitude cumuli. This would mean that the clouds are more easily triggered by weaker impulses (see concluding paragraphs of Section II) and that smaller buoyancy forces are required to produce comparable vertical speeds. Turbulence within trade cumuli could also be expected to be less than that in middle latitude clouds for the same ascent rates. This would happen because the in-cloud lapse rates need not be so much steeper than moist adiabatic. AUSTIN (1948) has pointed out that turbulence within a cloud should be greater the greater the departure of the in-cloud lapse rate from moist adiabatic, because an unstable state is thereby presented for the small-scale, moist adiabatic overturning near cloud center.

It was mentioned that the observed clouds in Fig. 4 may have slanted more than predicted by the Stommel-Malkus theory because of the omission of horizontal form drag from the model. Observations from the Thunderstorm Project also indicate that form drag may be important in reducing the relative horizontal cloud-air velocity. Some entirely different evidence presented by RIEHL et AL. (1951) regarding the transports in the subtropical cloud layer further support this possibility.

Transports by convective elements

Most of the work on cumulus clouds discussed so far emphasizes the effects of the environment upon the cloud. The data gathered by the University of Chicago Project Tyrena (reported on by RIEHL, YEH, MALKUS and LA SEUR, 1951) permitted for the first time framing the problem in reverse. Clearly, if the environment exerts a frictional force on the cloud, the cloud exerts an equal and opposite force on the environment. Also, according to the picture drawn above, the environment not only supplies drier air to the cloud, but by "detrainment" the cloud supplies moister air to the environment.

From the Tyrena observations it was possible to calculate effective large-scale momentum and moisture transport coefficients layer by layer for a section of the Pacific Trade. In the cloud layer the momentum "Austausch" was found to be significantly larger than the moisture "Austausch". Since the clouds themselves are the sole contributors to these coefficients within this layer (BUNKER et AL. 1949, have shown the turbulence in between clouds is at least an order of magnitude smaller than cloud scale) these data suggest that for equal gradients, trade cumulus clouds are far more effective transporters of momentum than of water vapor. If form drag is of roughly equal importance as entrainment in the horizontal momentum relations of the clouds, this observation is explainable qualitatively. If by means of pushing the air around itself, the cloud thereby exerts a force on the environment, it imparts some of its horizontal momentum to the surrounding air. It also exchanges horizontal momentum with the surrounding air by means of mixing or entrainment. It exchanges water vapor with the environment only by the latter process. Hence one might expect intuitively that the measured "eddy" viscosity for a convective layer might be considerably in excess of the "eddy" diffusivity. It can be shown analytically, even by a rather crude model, that if form drag and entrainment contribute friction forces (horizontal) of roughly equal magnitude on the elements of a convective layer, that this ratio comes out considerably greater than one. A required assumption is that the individual elements somehow overshoot their equilibrium positions and sink partially back down.

STOMMEL (1951) has demonstrated the overshooting of trade cumuli in the Caribbean, and RIEHL et AL. (1951) have further discussed how penetration of even a small fraction of the clouds into the trade inversion and later dissipation of their tops by mixing can provide sufficient moisture to account for the observed downstream rise in height and weakening of the inversion.

These latter calculations emphasize the tremendous amounts of energy continually pumped into the troposphere by the trade cumuli. The magnitude may perhaps be grasped by the following: If a one square kilometer area is 50 % covered by trade cumulus, only a small fraction of which need be actively rising at any one time, they can easily provide a net upward transport of latent energy in water vapor equal to that released by a 500 kg bomb of trinitrotoluene (3 000 cal/gm) exploding every minute. If this is summed up over all the tropical oceanic area normally covered by trade cumuli, a net upward transport of latent energy is given which is greater by a factor of roughly four or five, than the rate of kinetic energy dissipation by all the wind systems of the globe.

It has been strikingly pointed out by RIEHL (1950) however, that tropical convection does not uniformly feed energy into the atmospheric heat engine, but mainly in the easterly waves and polar troughs which, in passing, superpose strong convergence upon the flow. This large-scale convergence results in a greatly deepened "moist layer" and a tremendous diminution in the resistive forces operating against the growth of the cumuli. In the first place, the stable lid usually provided by the trade inversion is raised or removed. Second, net ascending motion in the region diminishes the required compensatory sinking and hence the reduction in buoyancy predicted by the slice method (CRESSMAN, 1946, has discussed this effect in detail) and finally, the growing clouds are surrounded by a deep layer of moist environment up to great heights so that entrainment is less effective in reducing their buoyancy.

How this energy, once made available in these disturbed regions to the upper subtropical atmosphere, is then injected into middle latitudes is being studied by Riehl and other investigators of the role of the tropics in the general circulation. It is now apparent, however, that cumulus clouds are important driving elements, and the forces restraining them are important controls, in the basic machinery of the atmospheric heat engine.

IV. Conclusion

In concluding, it can be seen that many more questions concerning cumulus cloud dynamics have been raised by this paper than have been answered by it. Many of these are framed in terms of specific sets of measurements which must be carried out. Consequently, the Woods Hole Oceanographic Institution has planned a new program of meteorological observations, to commence in the Spring of 1952. The principal observing tool is to be a large, slow-flying aircraft equipped with psychrograph, accelerometer, variometer, liquid water collector, drift sight, and cameras. By numerous flights through and near both trade and middle latitude cumuli, it is hoped to answer some of the existing questions and upon these answers to base new inquiries which are better evolved and more searching.

Acknowledgments

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Contribution No. 599

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THREE SPECIES OF FISHES, GENUS *SERIOLA*, IN THE WATERS OF CAPE COD AND VICINITY.—While engaged in a study of tuna made jointly by the U. S. Fish and Wildlife Service and the Woods Hole Oceanographic Institution, I had occasion during the summer of 1951 to observe three species of *Seriola* in Cape Cod waters, *Seriola zonata* (Mitchill), *Seriola dumerili* (Risso), and *Seriola fasciata* (Bloch).

The banded rudderfish (*Seriola zonata*) is a more or less regular summer visitor to the southern side of Cape Cod, but there have been few records of it from the north coast. In the summer and fall of 1950 and again in 1951, however, I often saw a dozen or more of this species among the landings from the traps in Cape Cod Bay at Barnstable. Twelve individuals obtained there from the trap of Captain John Vetorino ranged from 15 to 23 cm. in standard length, which is about the size-range of the others I have observed around the Cape. Captain Vetorino reports that the species has occurred regularly off Barnstable in recent years but was exceptionally abundant in the years 1949–1951. From one day's catch in this period he shipped two barrels of rudderfish to market. He also related that when the trap poles are pulled up in late October he frequently sees six or seven rudderfish gathered around each one, feeding on the animals which are shaken from it. Mrs. Marie Poland Fish, of the Narragansett Marine Laboratory, reports that in 1951 she obtained 15 specimens from traps near Point Judith, Rhode Island, and one from the Woods Hole Aquarium, all less than 20 cm. long.

The amberjack, (*Seriola dumerili*), is much less common in Cape Cod waters. Sumner, Osburn, and Cole (1913, Bull. U. S. Bur. Fish., 31 (1911): 751) listed this fish as occasional only. There are seven specimens from this area in the U. S. National Museum, and one in the American Museum of Natural History. All of these records date from many years ago, however, and I have been unable to find recent occurrences either in the literature or by questioning fishermen.

It therefore seemed of more than passing interest when we took 17 of these amberjacks while trolling for school tuna 10 to 15 miles south of No Mans Land (an island 17 miles south of the Massachusetts coast) in September, 1951. These fish ranged from 19 to 23 cm. in length, and despite their small size, they struck at tuna feathers and white marlin baits. They were concentrated under boxes, planks and patches of weed in a drift row. Several of these specimens are now at the Harvard Museum of Comparative Zoology.

A specimen of *Seriola fasciata* 19 cm. long was taken off No Mans Land along with the amberjacks. This little-known species was first figured by Bloch (1793, Ichthyologia, pl. 341) as *Scomber fasciatus*, with no locality given. Cuvier and Valenciennes (1833, Hist. Nat. Poiss., 9: 211) described the fish (under the name *Seriola fasciata*) and gave the first locality record for it (Carolina). Later authors who referred to it are: Gill (1863, Proc. Acad. Nat. Sci. Phila., 14 (1862): 442), who called it *Zonichthys fasciatus*; Jordan and Evermann (1896, Bull, U. S. Nat. Mus., 47: 904), who gave a description of *Seriola fasciata*, defined its range as West Indies to Charleston and listed Poey's names *Halactractus fasciatus* (1868) for the banded form and *Seriola semicoronata* (1860) for a phase without bands (which I have not seen); Jordan and Thompson (1905, Bull. U. S. Bur. Fish., 24 (1904): 237), who cited young specimens collected at Tortugas; Longley and Hildebrand (1941, Carnegie Inst. Wash. Publ. 535: 76), who placed this latter record in the synonymy of *Seriola dumerili*; and Fowler (1920, Proc. U. S. Nat. Mus., 56: 228; and 1936, Bull. Amer. Mus. Nat. Hist., 70: 679), who described 13 small specimens 10 to 12 cm. long taken off West Africa.

Museum specimens are not numerous. In addition to the No Mans Land specimen, the Harvard Museum of Comparative Zoology has one, 17 cm. long, from Cuba. Isaac Ginsburg has identified five at the U. S. National Museum, all less than 7 cm. long, as of this species. These are, respectively, from Long Island, N. Y., Cape Charles, Va., Beaufort, N. C., the Tortugas, Fla., and an unknown locality. Therefore, the capture of the Cape Cod specimen is noteworthy, for it is the most northern record for this species.—FRANK J. MATHER III, *Woods Hole Oceanographic Institution, Woods Hole, Massachusetts* (Contribution No. 599).

Contribution No. 600

ON THE STABILITY OF GAS BUBBLES IN SEA WATER[1]

By

JEFFRIES WYMAN, JR.,[2] P. F. SCHOLANDER,[3]
G. A. EDWARDS[4] AND L. IRVING[5]

ABSTRACT

Laboratory experiments have been performed to determine the rate of solution and the change in composition of air bubbles in stirred sea water as a function of depth (0–200 m) and temperature (1–27° C). At each depth the shrinking of the diameter is nearly linear. This rate of solution increases with increasing pressure up to a limiting value which is almost reached at a depth of 20 m. The rate of disappearance of a bubble is only imperceptibly influenced by temperature. When a bubble of air dissolves at a given depth it becomes richer in nitrogen until a final constant composition is reached. This final nitrogen percentage increases with increasing depth. Equations have been developed, based on the theory of diffusion, which satisfactorily account for the observed facts.

INTRODUCTION

There are many biological processes known where free gases are produced under water: gas bubble formation as a result of decomposition of organic material in lakes and swamps and in the sea, and gas bubbles from water plants as a result of photosynthesis. In many cases gases are carried by plants and animals either externally or internally or both. Gas bubbles also appear in the blood of higher organisms as a result of sudden decompression, giving rise to what is commonly called "bends." The mechanisms of gas bubble formation have been admirably treated by E. N. Harvey and coworkers (1944). The present study deals mainly with the fate of a bubble after it has been formed.

When gas is produced in the form of free bubbles, the partial pressures of the components within the bubbles are likely to be different from the partial pressures of the same components in the water, and hence gas exchange takes place. In sea water the partial pressures of the dissolved atmospheric gases are usually close to those in the atmosphere. This holds true very exactly for nitrogen at all depths

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(Rakestraw and Emmel, 1938; Hamm and Thompson, 1941). Any bubble in water will be at a total pressure of one atmosphere plus the prevailing hydrostatic pressure; hence it will finally dissolve. Since different gases have different solubility and diffusion characteristics, the composition of a bubble will change during the process. We have studied the rate of disappearance and the change in composition of dissolving gas bubbles at different depths by introducing bubbles into stirred sea water under pressures corresponding to depths as great as 200 m. Both disappearance rates and changes in composition have been found to follow simple physical laws that can presumably be applied also to other gases in less simple systems; the analysis we have given should be useful as a basis of calculation and interpretation to other investigators concerned with problems of gas exchange, respiration, and the like.

METHODS

Both low and high pressure systems were used to expose bubbles of gas to stirred water at different hydrostatic pressures and temperatures. The low pressure system is shown in Fig. 1B. A 300-cc glass bulb furnished with a vaccine stopper at one end and a piece of pressure tubing at the other is suspended on two bearing posts in a waterbath. The pressure tubing leads to a mercury leveling bulb which is suspended from a swivel so that the bulb can be elevated to any desired height. Through the injection port an air bubble can be introduced into the 300-cc bulb completely filled with water; the bulb is rotated by a simple drive so as to keep the bubble close to the center. The diameter of the bubble is measured through an ocular micrometer after stopping the rotation. The corresponding volume is found from an empirical calibration involving introduction of bubbles of known volume from a capillary syringe analyzer furnished with a hypodermic needle (Scholander and Roughton, 1942). The bubble is then withdrawn and analyzed with the same instrument. Pressures up to 20 m can be handled by this system.

For pressures corresponding to those at depths of 20 to 200 m, a pressure cylinder was employed which was fitted with a window and pressure gauge (see Fig. 1A). A large centrifuge tube containing about 300 cc of sea water is wedged into the cylinder. This tube is closed with a rubber stopper containing two holes, one for introduction of bubbles, the other connected with a syringe. The syringe ensures an anaerobic, sensitive pressure transmission between the nitrogen gas in the cylinder and the water containing the bubble. The desired pressure is furnished from a nitrogen cylinder. The instrument is rotated horizontally in a waterbath at a speed sufficient to keep the bubble near the center of the water column. After stopping the rotation, the diameter of the bubble is measured through the glass window by means of an ocular micrometer, using an empirical calibration as described for the low pressure system. The sea water used in the experiments was filtered and equilibrated with air at the desired waterbath temperature.

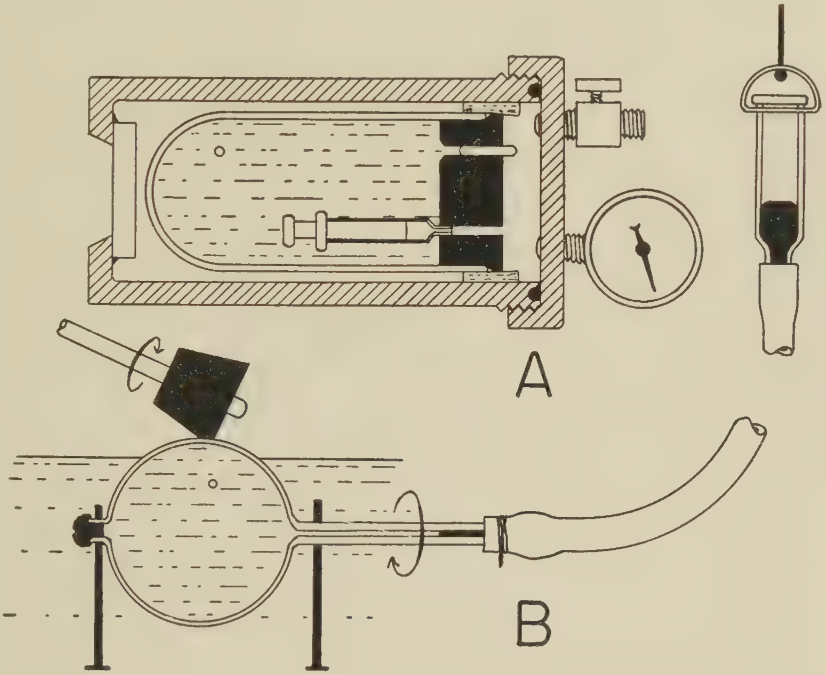

Figure 1. Methods for studying disappearance rate and changes in composition of bubbles under various hydrostatic pressures. A. The high pressure system. B. The low pressure system.

It should be pointed out that the amount of water used in both types of apparatus is so large that the solution of the bubble does not increase the concentration of dissolved gas enough to change the diffusion gradient by as much as one per cent.

RATE OF SOLUTION OF AIR BUBBLES IN RELATION TO PRESSURE

The first experiments were made to determine the rate of solution of a single bubble of air as a function of pressure. The results obtained are summarized as follows:

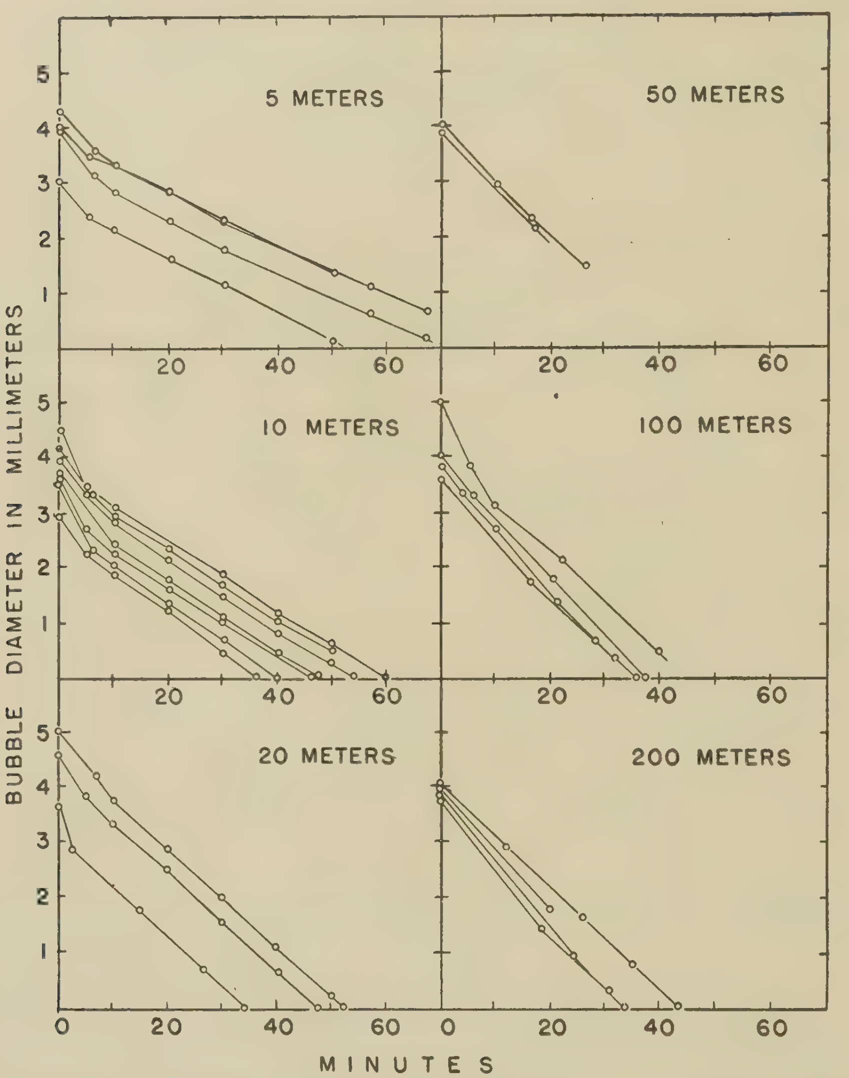

Figure 2. Rate of solution of air bubbles in sea water in relation to hydrostatic pressure (depth). Sea water was saturated with air at normal atmospheric pressure.

(a) As a bubble dissolves there is, at any given pressure, a nearly linear decrease in its diameter with time until it is too small to be seen. Actually the initial rate of shrinkage is always somewhat greater than the subsequent rate (Fig. 2).

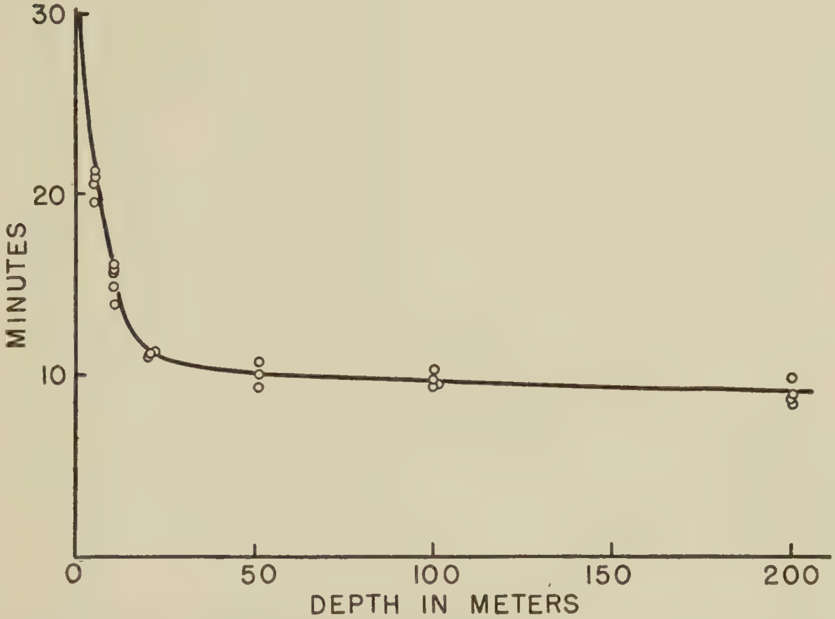

Figure 3. Minutes required to diminish bubble diameter 1 mm at various depths. Sea water was saturated with air at normal atmospheric pressure.

(b) The rate of solution increases with pressure but approaches an upper limiting value at high pressures. In Fig. 3 the average rate of disappearance of the bubbles is represented in relation to pressure.

(c) The rate of disappearance of a bubble does not vary significantly with temperature in the range from 1 to 27° C. Table I shows the figures obtained at a total pressure of 2 atm. (depth, 10 m).[6]

TABLE I

Temp., °C.	*Decrease of Bubble Diameter (mm/min.)*
1	.065–.068 (4 observations)
15	.065–.069 (7 observations)
27	.068–.069 (2 observations)

These results indicate that below 10–15 m the lifetime of an air bubble of given size should not vary much with depth and should be nearly proportional to the diameter. A bubble 2 mm in diameter would last about 20 minutes.

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[6] Of course the total pressure includes the pressure of one atmosphere which prevails at the surface.

This very simple behavior of a bubble can be accounted for, as a first approximation, by a correspondingly simple treatment based on the principles of diffusion. Due to the relative motion of the water and the bubble, we assume that the composition of the water in respect to dissolved gas is everywhere uniform except in a thin shell surrounding the bubble and that the gas in the bubble is uniform right up to the gas-water interface. The inner layer of water in the shell will be in equilibrium with the gas, and the whole of the diffusion gradient which causes the gas to pass from the bubble to the water will be supported by the shell. We assume further that this gradient is uniform throughout the shell. Also, we ignore the fact that the gas actually consists of oxygen and nitrogen, and we treat the situation as if only one kind of molecule were present with a single diffusion constant.[7] We introduce n to denote the number of moles of gas in the bubble; p, the pressure in the bubble; r, its radius; p_o, the partial pressure of the gas in the water everywhere outside the thin shell; t, the time; R, the gas constant; and T, the absolute temperature. Then, from the gas law:

$$n = \frac{1}{RT}\frac{4}{3}\pi r^3 p \,. \tag{1}$$

Also, from Fick's first law, which relates the amount of material which diffuses through unit area to the product of the concentration gradient and the diffusion constant:

$$\frac{dn}{dt} = -\,\delta 4\pi r^2 (p - p_o)\,. \tag{2}$$

In this expression δ is a proportionality constant which depends on: d, the thickness of the shell; on Δ, the diffusion constant of the gas in the water: and on α, the solubility of the gas in the water, in accordance with the relation

$$\delta = \frac{\Delta\alpha}{d}\,;$$

α is involved because of the necessity of converting the expression $(p - p_o)$ on the right of (2) into a concentration difference. By differentiating (1) with respect to time and combining the result with (2) we obtain the following expression for the rate of change of the radius of the bubble with time:

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[7] The uniformity of the gradient is a necessary consequence of Fick's second law of diffusion in any situation involving a steady state. In the present case the pressure of the gas within the bubble, which is the same as the hydrostatic pressure, remains constant, and the concentration of gas in the surrounding water is likewise constant. Therefore there must be a steady state as regards the concentrations of gas on the two sides of the diffusion layer except for changes of composition.

$$\frac{dr}{dt} = -\,RT\delta\,\frac{(p - p_o)}{p}\,. \tag{3}$$

The underlying basis for this result is that the pressure in the bubble depends on its volume whereas the amount of gas which escapes by diffusion depends on its surface.

Equation (3) accords with the results summarized above.

(a) It shows that for any value of p, corresponding to any given depth,[8] the value of $\frac{dr}{dt}$ should be constant. That is, the radius or diameter of the bubble should decrease uniformly with time.

(b) It describes the effect of pressure on the rate of disappearance of the bubble, at least as a first approximation. For example, at the surface $p = p_o = 1$ atm., and $\frac{dr}{dt} = 0$, as we know it must. At a depth of 10 m, $p \cong 2$ atm. At this depth

$$\frac{dr}{dt} = -\,\frac{RT\delta}{2}\,.$$

At 200 m, where $p = 21$ atm.,

$$\frac{dr}{dt} = -\,RT\delta\,\frac{20}{21}\,,$$

or about twice this. The limiting value of $\frac{dr}{dt}$ for very great depths is of course $-RT\delta$, or twice that at 10 m. This is close to what is observed (see Fig. 2 and Table II).

(c) It accounts for the fact that the rate of solution of a bubble is essentially independent of temperature. It will be seen that this rate is proportional to the absolute temperature and to the product of the diffusion constant Δ times the solubility α of the gas. Of the latter quantities the first (Δ) increases while the second (α) decreases with temperature, so that their product may be expected to remain roughly constant. No data appear to be available on the diffusivities of oxygen and nitrogen as a function of temperature, but the figures given in International Critical Tables show that from 10 to 21° the diffusivity of hydrogen in water increases from 4.3 to 5.2 cm²sec⁻¹. Over the same range the solubility coefficient of nitrogen decreases from .0186 to .0152. If the proportional change in the diffusivity of nitrogen were the same as that of hydrogen, the product $\Delta\alpha$ would change by only about one per cent between 10 and 21° and could be regarded as essentially independent of temperature. As a first approximation, the same conclusion may be applied to air. Since the range of absolute temperature covered by the experiments is small, we should therefore expect the rate of solution of the bubble to be nearly independent of temperature, as it is.

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[8] It should be emphasized that p is the total pressure of the gas in the bubble: i.e., 1 atm. at the surface. We take no account of the slight additional pressure due to surface tension. This is equal to $\frac{2\gamma}{r}$, in which γ is surface tension (for water, $\gamma = 72.8$ dynes/cm at 20°). For the smallest visible drop, of diameter say 0.1 mm, this will amount to 30,000 dynes/cm^2 (= 0.03 atm. = 30 mm water), which is too small to be of consequence. (Below 0.1 mm the pressure due to surface tension mounts rapidly and soon becomes the dominant factor.)

TABLE II

Meters	$-\frac{dr}{dt}$ (*cm/sec*) (*observed*)	$\frac{p - p_0}{p}$	$\delta \left(\frac{moles}{cm^2\ sec\ atm}\right)$ (*calculated*)
5	4.0×10^{-5}	1/3	5.0×10^{-9}
10	5.4×10^{-5}	1/2	4.5×10^{-9}
20	7.6×10^{-5}	2/3	4.8×10^{-9}
50	8.3×10^{-5}	5/6	4.1×10^{-9}
100	8.8×10^{-5}	10/11	4.0×10^{-9}
200	9.2×10^{-5}	20/21	4.0×10^{-9}

A more quantitative indication of the essential correctness of this interpretation is afforded by the constancy of the values of δ calculated by equation (3) from the experimental data, taking RT as 2.4×10^4 cc atm./mole, which corresponds to 20°. The constancy of the values of δ so calculated is shown in Table II, where the values listed for $\frac{dr}{dt}$ are those obtained by averaging the results of the various experiments, taking the final constant value of the rate in each case. It is seen that the values of δ are indeed fairly constant but that they show a real decrease with p. In all probability this is to be correlated with the fact that the bubble consists of two gases, oxygen and nitrogen, which, under the conditions of the experiment, leave the bubble at different rates and that the percentage of nitrogen in the bubble during the majority of its life is higher at the higher pressures. In the next section we shall deal with the question of the composition of the bubble and its effect on the rate of solution.

Added confirmation of the simple picture given above is provided by observations on the rate of disappearance of an air bubble at 2 atm. (10 m) into degassed sea water. The observed rate is $\frac{dr}{dt} = 0.06$ mm/min. This is the same, within the limits of error, as the observed value for 100 or 200 m (0.055 mm/min.). This is as it should be, for in the case of degassed water, $p_o = 0$ and (3) reduces to

$$\frac{dr}{dt} = -RT\delta ,$$

which is the same as the limiting form approached by the equation for great depths ($p \rightarrow \infty$) when $p_o = 1$.

Before we conclude this section it is important to point out that the results on the rate of disappearance of an air bubble in water are in general agreement with much cruder results on the rate of accumulation of gas in a cavity produced by suddenly and forcibly withdrawing and briefly holding back the piston of a syringe while the nozzle is kept closed. The amount of gas which would be expected to enter the cavity produced under these conditions may be roughly estimated by means of equation (3). For this purpose we set $p = 0$ and $p_o = 1$. Then, if we denote the surface area of the cavity by A, the number of moles of gas which enter it in time t should be given by

$$\int_o^t \frac{dn}{dt}\, dt = A\delta p_o t\,. \tag{4}$$

The volume which these molecules would occupy at a pressure of 1 atm., corresponding to the condition when the piston of the syringe is released, is

$$RTA\delta p_o t\,. \tag{4.1}$$

On the basis of Table II, $RT\delta$ may be taken as 10^{-4} cm/sec. Several experiments were made to test this prediction under conditions for which A was estimated to be in the neighborhood of 16 cm^2, though this figure was probably too low due to the irregularity of the cavity associated with the splashing of the liquid. From the figures just given, the calculated volume of gas which should have entered the cavity per second turns out to be approximately 1.6×10^{-3} cm^3. The observed amount is about twice this, but in view of the uncertainties involved in the calculations, the agreement may be regarded as satisfactory and may be taken as evidence in support of the fundamental correctness of the interpretation. These results on the accumulation of gases in a cavity by diffusion from the surrounding medium are of interest in connection with various respiratory problems.

CHANGES IN COMPOSITION ACCOMPANYING SOLUTION OF GAS BUBBLES

When the gas obtained from freshly formed cavities is analyzed it contains significantly more oxygen than the 21% characteristic of air. In fact, analyses made as soon as possible after formation of a cavity yield values up to 35% oxygen.[9] Correspondingly it is found that as bubbles of air introduced into water diminish in size under excess pressure they become poorer in oxygen and richer in nitrogen. These two observations really represent the same phenomenon, namely the different rates of passage of oxygen and nitrogen across the diffusion layer at the surface of the bubble (cavity). As we have already suggested, certain small discrepancies between the observations and theory encountered in the preceding section are probably attributable to this phenomenon. In order to explore this subject, experiments were carried out to determine the changes in composition accompanying the solution of gas bubbles in water, and, in particular, the effect of pressure on the phenomenon.

The bubbles, consisting either of air or of an arbitrary mixture of oxygen and nitrogen, were placed in either one of the pressure chambers previously described and were allowed to dissolve for a given time before being withdrawn for gas analysis. The initial size of the bubble used varied somewhat, but it was in the neighborhood of 3.5–4 mm in diameter. The results are shown in Fig. 4, which illustrates quantitatively the way in which the bubbles always become richer in nitrogen as they diminish in size. By the time they are disappearing they ap-

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[9] In accordance with considerations to be developed presently we should expect the amount of oxygen in a freshly formed cavity to be half that of nitrogen; in other words, the gas should be 33⅓% oxygen. This follows from the same line of reasoning involved in equations (4) and (4.1). We should expect the ratio of oxygen to nitrogen in the cavity, before any gas has had a chance to escape, to be given by

$$\frac{\delta_1}{\delta_2}\frac{p_{1o}}{p_{2o}} = 2 \times \frac{0.2}{0.8} = \frac{1}{2}.$$

(Subscripts 1 and 2 refer to oxygen and nitrogen respectively.) The value 2 for the ratio $\frac{\delta_1}{\delta_2}$ is based on considerations given later in this section.

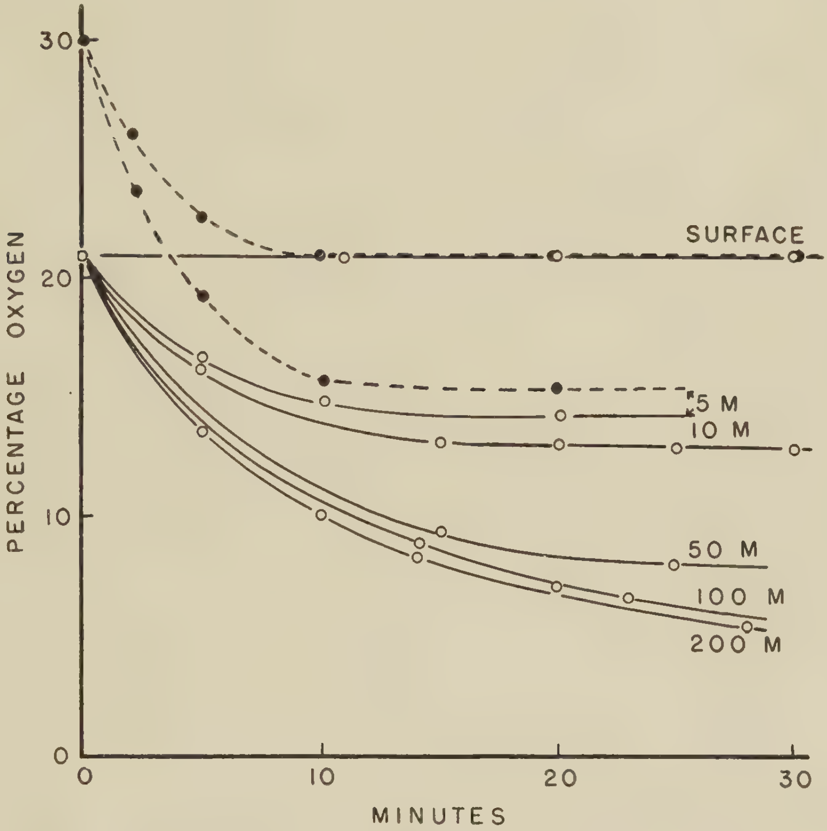

Figure 4. Change in composition of bubbles as they dissolve at different pressures (depths) in sea water saturated with air at normal atmospheric pressure. The initial diameter of the bubbles studied varied from approximately 3.4 to 4 mm.

pear to have attained a nearly constant composition. This composition is the richer in nitrogen the higher the pressure.

The physical explanation of the phenomenon is simple. It rests on the fact that the diffusion constants of oxygen and nitrogen are nearly the same but that the solubility of oxygen is about twice that of nitrogen.[10] Let us consider the case of an air bubble suspended in water saturated with air at atmospheric pressure. If the pressure in the bubble is one atmosphere, as at the surface, no gas will pass into the liquid phase, for the system is at equilibrium (see Fig. 2). There will be no concentration gradient anywhere to produce diffusion. However, if the pressure is raised, the concentration of oxygen at the air-water interface, and consequently the concentration gradient across the diffusion layer, will increase more in proportion to the amount of gas in the bubble for oxygen than for nitrogen, owing to the greater solubility of oxygen. Consequently, since the diffusion constants of the two gases are the same, the percentage loss of oxygen from the bubble will exceed that of nitrogen and the bubble will become richer in nitrogen.

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[10] At 19° the diffusivity of nitrogen in dilute aqueous solution is close to 1.9 and at 18° that of oxygen is also close to 1.9 $cm^2\ sec^{-1}$ (International Critical Tables). The solubility coefficient of N_2 is .0155 and that of O_2 is .0310 in H_2O. These figures refer to volumes of gas (measured at 0 and 1 atm.) dissolved by 1 volume of water when the partial pressure of the gas is 1 atm.

It is worth-while to formulate the situation mathematically in terms of our simplified hypothesis. On the whole the result agrees so well with the facts that it suggests that our picture of the physical factors involved is correct and lends confidence to any inferences based on that picture. In this formulation, subscript 1 refers to oxygen and 2 refers to nitrogen, and x is introduced to denote the mole fraction of oxygen in the bubble. Otherwise we use the same notation as before. The situation is governed by the following equations:

$$n_1 = \frac{1}{RT}\frac{4\pi r^3}{3}xp, \quad n_2 = \frac{1}{RT}\frac{4\pi r^3}{3}(1-x)p\,, \tag{5}$$

$$\frac{-dn_1}{dt} = \delta_1 4\pi r^2(xp - p_{1o}), \quad \frac{-dn_2}{dt} = \delta_2 4\pi r^2[(1-x)p - p_{2o}]\,. \tag{6}$$

If we differentiate (5) with respect to time we obtain:

$$\begin{aligned} \frac{dn_1}{dt} &= \frac{4\pi r^2}{RT}xp\frac{dr}{dt} + \frac{4\pi r^3}{3RT}p\frac{dx}{dt}\,, \\ \frac{dn_2}{dt} &= \frac{4\pi r^2}{RT}(1-x)p\frac{dr}{dt} - \frac{4\pi r^3}{3RT}p\frac{dx}{dt}\,. \end{aligned} \tag{7}$$

Equations (6) and (7) provide four relations between the five infinitesimals dn_1, dn_2, dt, dx, and dr. They may be combined to eliminate any three of these, leaving an equation between the remaining two. Our interest is of course limited to t, x, and r. If the two infinitesimals are chosen as dr and dx, we obtain, after taking account of the fact that $\delta_1 = 2\delta_2$,

$$\frac{-3dr}{r} = \left[\frac{xp + p - p_{2o} - 2p_{1o}}{x^2p - x(p + p_{2o} + 2p_{1o}) + 2p_{1o}}\right]dx. \tag{8}$$

Similarly, if they are chosen as dr and dt, we obtain

$$-dr = RT\delta_2 \left(\frac{xp + p - p_{2o} - 2p_{1o}}{p}\right) dt. \tag{9}$$

Finally, if they are chosen as dx and dt, we obtain

$$dx = \frac{3RT\delta_2}{rp}\left[x^2p - x(p + p_{2o} + 2p_{1o}) - 2p_{1o}\right] dt. \tag{10}$$

Of these three equations only (8) is suitable for integration, and it is apparent that the significant variable in determining x is r, not t. Nevertheless (9) and (10) are of interest also. For example, (10) makes it possible to calculate the limiting steady value of the composition of a bubble as it dissolves $\left(\frac{dx}{dt} = 0,\ r \neq 0\right)$ and to see how this varies with p, p_{2o}, and p_{1o}. If we assign to p_{1o} and p_{2o} the values corresponding to atmospheric air, we verify that the equilibrium composition of the bubble is richer in nitrogen the greater the pressure p, as we find it to be.

If equation (8) is written in the form

$$\frac{3dr}{r} = \left(\frac{x + a}{b^2 - (x + c)^2}\right) dx, \tag{11}$$

it may be integrated to give

$$\log r = \frac{1}{6}\left[\frac{(a - c)}{b} \log \left(\frac{b + c + x}{b - c - x}\right) - \log \{b^2 - (x + c)^2\}\right] + \text{const.} \tag{12}$$

Since, according to definition, the quantities a, b, and c are known functions of p, p_{1o}, and p_{2o}, (12) may be used to calculate pairs of values of x and r/r_o for different conditions (r_o being the initial radius of the bubble). Of course these must include a specification of the value of x for $t = 0$ ($r/r_o = 1$), i.e., the initial composition of the bubble. If we are interested in the case of an air bubble dissolving at pressure p in water saturated with air at atmospheric pressure we may set $p_{1o} = 0.2$ atm. and $p_{2o} = 0.8$ atm. Theoretical curves calculated for this case are shown in Fig. 5, together with corresponding experimental points obtained by the methods already described. The agreement, on the whole, is satisfactory and there is little doubt that the interpretation we have given provides the essential explanation of the main phenomenon; i.e., the gradual increase in the nitrogen content of the

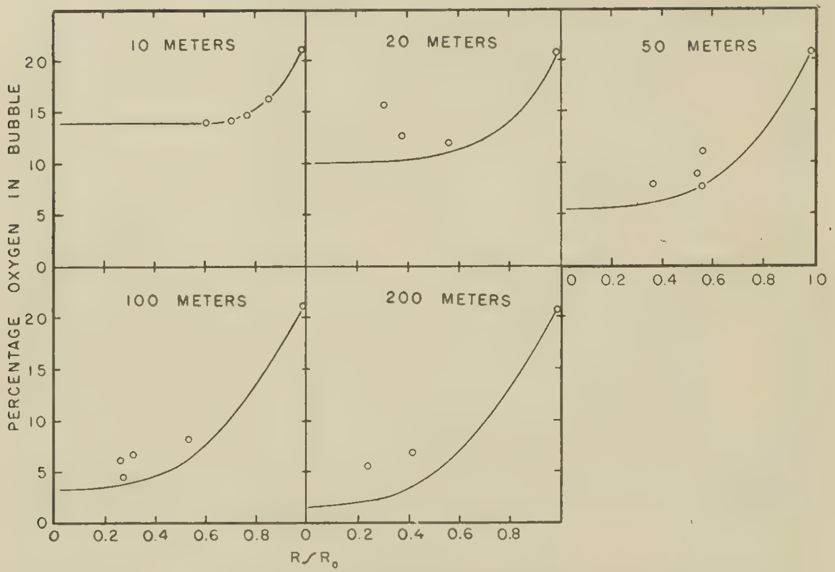

Figure 5. Changes in composition of air bubbles dissolving at different pressures (depths) in sea water saturated with air at normal atmospheric pressure. The abscissa gives the ratio of the radius of the bubble at the time the analysis was made to the initial radius of the bubble.

bubble as it dissolves towards a limiting steady value is greater as the pressure (depth) increases.

By joint use of equations (9) and (12) it is a simple matter to calculate how the rate of shrinkage of the bubble should vary with size and composition and depth. Such calculations are given in Table III, and they serve to explain the fact that at all pressures the initial value of $\frac{dr}{dt}$ is always greater than the later values, as shown by the data given in Fig. 2. They also explain why the values of $RT\delta$ calculated from (3) and shown in Table II are not constant but decrease with pressure. Physically, of course, this is explained by the fact that initially, when the bubble is relatively rich in oxygen, it shrinks more rapidly due to the fact that the rate of loss of oxygen is greater than that of nitrogen.

From the values of $-\frac{1}{RT\delta_2}\frac{dr}{dt}$ given in Table III and from the values of $\frac{dr}{dt}$ given in Table II (representing final rates), δ_2 (referring to nitrogen) may be calculated and then the thickness of the water shell

TABLE III

$\frac{r}{r_o}$	x	$-\frac{1}{RT\delta_2}\frac{dr}{dt}$	$\frac{r}{r_o}$	x	$-\frac{1}{RT\delta_2}\frac{dr}{dt}$
10 m			20 m		
1	.21	.61	1	.21	.81
0.5	.140	.54	0.5	.110	.71
0.0	.136	.54	0.0	.103	.70
50 m			100 m		
1	.21	1.01	1	.21	1.10
0.5	.072	.871	0.5	.055	.945
0.0	.058	.859	0.0	.033	.923
200 m					
1	.21	1.21			
0.5	.048	.99			
0.0	.018	.96			

surrounding the bubble. We first find that $RT\delta_2 = (10 \pm 0.5)^{-4}$ cm/sec. From this, taking $RT = 2.4 \times 10^4$ cc atm./mole, we obtain $\delta_2 = 4.2 \times 10^{-9}$ moles/cm²/sec./atm. (δ_1 is twice this, or 8.4×10^{-9}). However, $\delta_2 = \frac{\Delta_2\alpha_2}{d}$. At 20°, $\Delta_2 = 2 \times 10^{-5}$ cm²/sec. and $\alpha_2 = 6.9 \times 10^{-7}$ moles/cc/atm. Consequently, $d = 3.3 \times 10^{-3}$ cm. It should be realized that the picture of a sharply defined water shell supporting a uniform diffusion gradient surrounding the bubble is artificial. The bubble behaves as if this were the case, but this simply means that the mixing of the water is practically complete up to a distance from the air-water interface of the same order of magnitude as the calculated thickness of the shell.

SUMMARY

Observations on the rate of solution of gas bubbles in water are described and are shown to be in close accord with equations based on the theory of diffusion. As an air bubble dissolves in water saturated with the atmosphere, the rate of decrease in diameter with time is nearly constant and increases with depth up to a limiting value. However, there is a slight decrease in the rate of solution with time, and this is associated with a change in composition, the bubble becoming richer in nitrogen as it approaches a limiting composition. When a bubble is formed in water saturated with air as a result of cavitation, it is initially much richer in oxygen than air, as would be predicted. Theoretically, the percentage of oxygen to be expected in such a bubble at the moment of formation is 33⅓%. Actually the highest observed value was 35%.

The equations developed in connection with these observations are of general applicability and should be of use in the analysis of various respiratory and other physiological problems involving aquatic organisms. They may also apply in certain problems of physical oceanography.

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On the Role of the Ice off Iceland in the Decadal Air Temperatures of Iceland, and some other Areas.1)

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A. Introduction.

Evidence from numerous investigations in the past two decades, or perhaps longer, points decisively to a marked rise in the temperature of the air over wide areas and to a smaller but no less significant rise in the temperature of the northern North Atlantic Ocean. Little, if anything, has been said about the possible causes of this rise and whether the relatively high temperatures may continue and for how long.

While a fully successful attack on this problem may not be possible until such time as we possess more adequate data, we can attempt to formulate the broad character of the problem for the North Atlantic and adjacent regions, for which a considerable body of data has recently been published, and to obtain indications of certain trends in the air and water circulation that could be checked with more comprehensive data as they become available.

The character of the ice off Iceland, which has been reliably observed for a long period and which over longer periods reflects in some measure both the changes in the limits of the Arctic ice mass and in the southward transport of polar water, permits in conjunction with the available long series of temperature data an analysis of a major phase in the fluctuations in the circulation of the northern North Atlantic and adjacent areas and, accordingly, will form the subject

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of the present investigation. As the problem before us in a deeper sense involves the problem of the origin of the variations in the general circulation, a discussion of the latter will be given first.

B. Origin of Variations in the General Circulation.

1. The Sun.

Admittedly, barring the possible influences of volcanic irruptions and other rare and singular occurrences in nature, the basic cause of all observed changes in the general circulation, and in the climate and weather, is the variations in the sun's radiation.

The hydrosphere, however, because of its large heat capacity and its slow rate of absorption and giving off its heat, budgets the heat it initially derives from the sun, to a considerable extent independently. In a much smaller measure this is also true of the atmosphere and instead of a single major source of energy affecting the general circulation — the sun — we have as indirect sources also the hydrosphere and atmosphere.

While we may expect a fall in the pressure in low and a rise in high latitudes following, it may be assumed, a poleward outflow of air from the equator during periods of high sunspot activity, should the atmosphere and hydrosphere call for trends in pressure opposite to that called for by the sun, the normal relation of pressure with increase in the sun's radiation could not be expected to emerge.

Thus, following a rise in the sun's radiation we may have either (a) the required trend in the circulation strongly developed if the trends called for by the hydrosphere and atmosphere are in phase with that of the sun, (b) the same trend moderately developed if the latter two media are in the neutral state, and (c) the trend poorly developed or entirely absent if the hydrosphere and atmosphere exert an influence in the direction opposite to that exerted by the sun, unless the rise in the sun's radiation is strong enough to overcome these influences.

The above, it is suggested, explains why comparisons of the sunspot number with the pressure, for example, have yielded results that differ substantially with a particular maximum or minimum sunspot period (as the general circulation is in or out of phase with that called for by the sun's variations) and why the division of the sunspot periods into major and minor maxima (among others, Hanzlik, 1930; Clayton, 1934; Willett, 1949a; Wexler¹), 1950) and the

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¹) This author obtained significantly different results for the summer and winter seasons, and his results, furthermore, did not agree too well with Clayton's for an identical period (1910—20).

However, while an increase in the sun's radiation may be expected to produce equal pressure falls in winter and summer in equatorial latitudes, the called-for poleward flow of air in the northern hemisphere would be aided by the normal transport from the southern to the northern hemisphere in winter but impeded by the oppositely directed flow in summer. Thus the consistently greater effect found by Wexler (loc. cit) in winter than in summer for the average sunspot maximum as compared with the average sunspot minimum (see his Fig. 7, not reproduced here) was further differentiation made from a consideration of the degree of sustained high and low sunspot activity (Schell, 1943) produced results that were, in general, more consistent with the relationship expected than with undifferentiated periods of high and low sunspot activity. Yet while these and other studies have given support to the thesis that with high sunspot activity, etc., the pressure is on the whole lower in equatorial and higher in high latitudes than with low sunspot activity, etc., since the actual pressure patterns associated with the individual periods of high and low sunspot activity, etc., differ very markedly from each other, the quasi-independent control exercised by the hydrosphere and atmosphere on the general circulation appears, in general, considerably greater than the direct control exercised by the sun. It may be concluded that the analysis of the relationships within and between the hydrosphere and the atmosphere is a primary condition for elucidating the relationships between the sun's variations and the contemporary and following changes in the general circulation. The difficulty, it may be added, is not the "smallness" of the observed changes in the sun's radiation as it is sometimes assumed. Actually, we do not know the magnitude of change required in the sun to produce the observed large changes in the higher and small changes in the areally much greater lower latitudes. Again the "small" changes of the sun's radiation measured at the surface of the earth do not generally represent too well the actual changes in the sun's radiation. We know from the very significant correlations of sunspot activity with magnetic and auroral phenomena, for example, that the sun undergoes marked changes consistent at least with the monthly, seasonal, and longer-period sunspot numbers.

2. Hydrosphere and Atmosphere.

Having found it necessary to conclude that the origin of the circulation changes discussed here, appears intimately bound up with the preceding variations in the hydrosphere and atmosphere, we can now consider the possible approaches to derive the circulation interconnexions in question.

We have our choice, on the one hand, of a rigid mathematical treatment which in order not to overcomplicate the mathematics, involves an idealized state of the atmosphere, and on the other, a treatment determined from rough physical hypotheses or circulation indices whose validity depends on their withstanding the test of large accumulations of non-arbitrarily selected data. As the latter approach more closely deals with the actual conditions in the atmosphere than the former, it will be used here.

An index of circulation used not infrequently in recent years is the circumferential pressure difference between latitudes 35°N. and 55°N.,

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to be expected. Also, the lack of a better agreement between Wexler's and Clayton's findings — actually both found the expected higher pressure in the high latitudes — appears due to the different treatment and significantly different collections of data used by the two authors.

freely referred to as the "zonal index". For variations in the circulation extending over longer periods, this index may indeed be reasonably assumed to reflect an expanding or contracting polar anticyclone and the major changes in the climate and weather in the higher latitudes at least as suggested by Willett (1949b).

It does not appear, however, that for intervals of only a day, week, month, season, and perhaps longer, this circumlatitudinal pressure difference necessarily reflects a uniformly expanding or contracting circumpolar vortex and a true zonal circulation.

From the fact that when the North Atlantic air circulation (North Atlantic Oscillation) is more intense than usual, the North Pacific Oscillation is as frequently in as out of phase with the former (Walker and Bliss, 1932) and similarly, that when the Siberian High is better developed than usual this is not necessarily the case with the North American High, it may be concluded that circumlatitudinal pressure differences quite often represent deeply conflicting tendencies in the zonal circulation and cannot therefore be expected to yield any extensive correlation with the weather. This conclusion is supported by a number of studies (Willett, 1949a and others) which indicate little correlation on the whole of circumlatitudinal pressure differences with various synoptic or statistical systems. The fact that the results obtained were mostly negative suggests the desirability in general of treating the general circulation as a system of natural, more or less independent components of the whole, rather than treating conditions over an entire belt of latitude as a single unit. It is essential, however, that the treatment proposed should involve a physical principle that will permit broad and consistent application of the results obtained to the actual weather. In the following a principle that leads to physically based space-time-lag interrelations in the circulation will be stated more fully (see Schell, 1947).

C. The Principle of Dynamic Persistence.

Dynamic Persistence is a principle that covers relationships of the weather in certain areas that are synoptically linked to conditions in distant areas which have marked simple or local persistence. Dynamic Persistence thus introduces a physical linkage of space-time-lag variations in the circulation and operates as follows.

Given an area B whose weather during a given season is synoptically linked to another area A and, further, conditions in area A are markedly similar to those the season before (local persistence), the weather in the first-named area, B, must, it follows, be related to conditions in area A, also the season before. For example, if it can be shown that the pressure in an area A has (1) marked persistence from, say, the September—November to the December—February quarter and that (2) the December—February pressure and by association, also the storminess and precipitation in this area is synoptically linked to the pressure, storminess, and precipitation in area B the same season, it must follow that conditions in area B during December—February are related to the pressure in area A also the quarter before, i.e., September—November.

Thus area A, in addition to exhibiting the property of local or simple persistence, may be said to possess also the property of influencing in September—November the precipitation, etc., in area B the following quarter through (1) persistence in pressure from September—November to December—February and (2) movement of storms from area A to area B during December—February. The term Dynamic Persistence, in the sense of an effect of local persistence being translated to the weather of another area, is used to define this property. The time difference involved in Dynamic Persistence makes possible in theory also the foreshadowing of conditions in area B from those in area A, before.

Of the several Dynamic Persistence relationships identified thus far (Schell, 1947), the relationship of September—November tropical Australasia pressure (Manila, Port Darwin, etc.) to the following December—February quarter rainfall in the Philippines, south-east China, southern Japan, Midway, Wake, Hawaii, Aleutians, south-west Canada and north-west U. S. A., as well as south-east U. S. A. — through the inverse association between the storms in the north-west and those in the Gulf of Mexico — is the more remarkable. This large group of synoptically linked space-time-lag interconnexions arises from (a) the persistence in tropical Australasia pressure from September—November to the following December—February, (b) the relation of pressure to storminess in that general area, and (c) the movement of the storms across the North Pacific to North America.

The several Dynamic Persistence relationships outlined thus far are but a few of this class that may be presumed to exist in the general circulation. It also follows from the interrelation of different circulation systems that for areas with no Dynamic Persistence, relationships of a derivative nature may be expected. Thus, referring to the relationship with tropical Australasia pressure above, when the winter precipitation is above normal in the north-west and below normal in the south-east U. S. A. following below-normal pressure (increased storminess) in tropical Australasia the precipitation in the areas in between north-west and south-east U. S. A. is close to the normal.

In weighing the possible usefulness of Dynamic Persistence, as a basis for physically conceived space-time-lag relationships, we might have wished first to turn to the hydrosphere. Marked persistence is generally more characteristic of the oceans than the atmosphere, and we may, therefore, expect a large array of space-time-lag relationships within the oceans and because of the oceans' interaction with the air, also with the following climate and weather. A prime requisite for the examination of a rough physical theory is, we must insist, the use of long series of non-arbitrarily selected data. Consequently the oceans unfortunately cannot generally figure very prominently in this respect today. A notable exception are the variations in the sea ice from the

North Atlantic—Arctic, the record of which in the case of the waters off Iceland extends in some detail to the end of the 18th century and in a more general form, considerably earlier (Koch, 1945).

D. Role of Polar Ice in the Circulation.

1. General Remarks.

The suggestion that polar ice plays an important role in the weather dates back considerably but it was not till later that an attempt was made by Wiese (1924) and others to develop this idea into an inclusive hypothesis which they sought to verify with the rather sparse and short series of data available at the time.

Briefly, an increase in the ice in the Arctic and simultaneously in the Antarctic[1]) is assumed to occur when the general circulation weakens and less warm, moist air is transported to the polar latitudes. This causes a greater cooling and bigger ice formation there. Conversely, a decrease in the ice occurs with an intensified circulation and an increased transport of warm moist air to polar latitudes.

Wiese (loc. cit.) further postulated that as a result of the marked persistence in hydrological processes due to the greater stability in the movements of large water masses and the large heat capacity of water, we may expect also relationships between the ice and the following circulation, etc., in the immediate area of the ice, and because of interaction of the circulation of higher with that in lower latitudes, also with the following weather in "adjacent" areas. Thus as the ice is presumed to be determined initially by the change in the general circulation, relationships may be expected between the ice and the preceding, following, and contemporary circulations, etc., in the immediate and adjacent areas.

In so far as relationships of the ice with the following circulation are concerned, it is not suggested that these are due to the melting of the ice, although this influence appears not negligible (Smith, 1931); nor is it suggested that the variations in the ice together with the much greater variations in the volume of polar water which the ice over longer time-intervals must reflect, could alone account for the observed changes in the circulation. Rather, severe ice conditions, for example, in the North Atlantic—Arctic together with the large increases in the volume of cold water flowing from the Arctic appear to mean an intrusion of considerable masses of polar water to the south[2]) and hence, a southward displacement of the zone of convergence of the cold polar and North Atlantic warm water that is related also to the North Atlantic mean storm track, precipitation, etc. (Wiese, loc. cit., Brooks and Quennel (1928), Scherhag (1937), Schell (1940, 1947)).

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[1]) The verification of this is one of the principal aims of the current British-Norwegian-Swedish Antarctic Expedition.

[2]) No data are available for the variations in the southward transport of polar water, which, according to Zubov's (1945) estimates for the East Greenland Polar Current between Spitsbergen and Greenland (at 81°N.), amounted to 80,000 km^3. in 1937. It may be assumed from the fact that there was little or no ice off Iceland from 1919 to 1940 that the volume of polar water reaching Iceland, etc., during that period was very much less than in the period from 1865 to 1874, when Iceland was almost completely surrounded by ice for months at a time.

The effects of the marked variations in the limits of the Arctic ice mass as well as in the southward transport of polar water, etc., may be secondary but nevertheless sufficient, especially following prolonged periods of either severe and light ice and a greater or smaller influx of polar water, to weaken or intensify existing trends in the circulation. As a result, warm periods, for example, may become relatively cooler than might be expected were it not for severe ice conditions prevailing, or warmer if little or no ice is present.

2. Ice off Iceland.

The relationship of the mean April—August ice area of the Greenland Sea to the following October—December precipitation in northwestern Europe through a latitudinal shift of the North Atlantic storm track, etc., (Schell, 1947) may be considered as but one of a broad group of Dynamic Persistence relationships involving the ice of the Arctic. Relationships involving variations extending over periods longer than a few months may also be assumed. As the aim of the present investigation was in part to formulate the problem of longer-period variations in the circulation, etc., of the northern North Atlantic and adjacent areas, only the latter type of variations in the ice, etc., will be dealt with here.

The longest records of Arctic ice are from off Iceland rather than from the Greenland Sea as a whole, which go back to 1877 only. Consequently, the Iceland observations will be used. The data will be compared first with the long records of temperature from Iceland, northern Europe, and New Haven, Conn. (U. S. A.). Later an attempt could be made to integrate into the comparison with the ice also the shorter records of storms, precipitation, etc. The comparison of the ice with the temperatures will, in keeping with our interest in the general role of polar ice in the circulation, etc., include also the temperatures preceding the longer-period variations in the ice.

E. Method of Analysis.

The ice and temperature data have been averaged by decades. Obviously, some periods of shorter duration of severe ice will be combined with some of light ice and, hence, certain relationships may be obscured. Broad trends, however, may be detected and later on attempts can be made to delineate still other trends.

The use of annual mean temperatures rather than temperatures for the ice season alone may be criticized. Nevertheless, there is considerable justification for this procedure, when one considers the persistence of given water conditions for longer periods than indicated by the presence of ice. Thus, although the ice season off Iceland lasts only for a period of several months (i.e., from late winter or early spring to late spring or early summer), the flow of cold polar water, which likewise affects air temperatures, does not necessarily commence with the appearance of the ice or cease with its disappearance. Hence, in the absence of more information on the fluctuations in volume of the various water masses, it is actually impossible to determine the precise effect of the ice conditions alone.

F. Data.

Because significant temperature data (see below) for one of the more important areas are not available prior to 1831, the present study is based on data accumulated since that time. Thus, detailed data for 11 decades (1831—1940) and approximate information for one other (1941—50) are considered here. The last decade will be treated separately (see below).

1. Ice.

It is generally agreed that the ice observations off Iceland were carefully made and that they give a fairly accurate idea of actual ice conditions because of its importance in the lives of the inhabitants there. The severity of the ice season off Iceland is usually recorded as the number of days or weeks the ice was observed off the coast and by its relative abundance. This has been tabulated by Meinardus (1906) and more recently by Koch (loc. cit.) from observations of Thoroddsen (1884) and from records in „Isforholdene i de Arktiske Have", published by the Danish Meteorological Institute. Koch also included the extent of the ice surrounding the island. In general, the longer the ice is observed off Kap Horn on the north-west coast, the heavier it is and the farther it spreads eastward along the north coast, thence southward along the east coast and westward along the south coast.

For discussion of the causes of the ice situation off Iceland, the reader is referred to the literature. It should be noted, however, that prolonged periods of severe ice conditions off Iceland, such as those considered here, can, it is believed, occur only when the Arctic ice pack is well developed and a large quantity of ice is carried via the East Greenland and the East Icelandic Polar Currents to the vicinity of Iceland.

The Icelandic ice data presented here (Table I) consist of annual estimates taken from Koch's graph (1945, Fig. 103). These figures over a period of years show the number of weeks with ice multiplied by the number of areas where the ice was observed along the Icelandic shores. The mean annual values are given for each decade from 1831 in Table II. A comparison of the latter with those of Meinardus (loc. cit.) up to 1900 are remarkably alike except for those of the first decade (1831—1840). According to Meinardus this period was one of moderate ice, but according to Koch's analysis of Thoroddsen's data, it was a severe one. The latter, I believe, is more accurate

Table I. Estimates of Annual Ice Severity off Iceland given by the Number of Weeks multiplied by the Number of Areas with Ice around Iceland Each Year during 1831—1940 (after Lauge Koch, 1945).

Year	Ice Severity	Year	Ice Severity	Year	Ice Severity	Year	Ice Severity	Year	Ice Severity	Year	Ice Severity
1831	5	1851	0	1871	10	1891	49	1911	94	1931	0
2	1	2	0	2	20	2	131	2	0	2	6
3	0	3	6	3	7	3	0	3	0	3	0
4	24	4	6	4	94	4	0	4	26	4	0
5	207	5	95	5	0	5	38	5	47	5	0
6	0	6	15	6	60	6	83	6	2	6	0
7	137	7	36	7	2	7	3	7	3	7	0
8	4	8	35	8	60	8	3	8	34	8	12
9	5	9	96	9	3	9	2	9	1	9	0
1840	184	1860	64	1880	9	1900	0	1920	0	1940	0
1	0	1	0	1	160	1	2	1	2		
2	0	2	6	2	113	2	138	2	0		
3	2	3	32	3	15	3	9	3	1		
4	0	4	0	4	0	4	0	4	1		
5	0	5	17	5	6	5	2	5	0		
6	0	6	174	6	60	6	3	6	0		
7	0	7	96	7	89	7	15	7	0		
8	3	8	40	8	251	8	2	8	1		
9	0	9	125	9	0	9	0	9	7		
1850	4	1870	107	1890	0	1910	0	1930	0		

because he included the extent of the ice surrounding the island. Accordingly, in this report, that decade (1831—1840) is considered to have been one of severe ice.

Fortunately, the series just described contain three decades (1841—1850, 1921—1930, 1931—1940) which are characterized by little or no ice and three others (1831—1840, 1861—1870, 1881—1890) in which severe ice conditions (Table II) prevailed. In addition to these there is also a decade with light ice (1841—1850) following one of

Table II. Estimated Mean Annual Ice Severity off Iceland by Decade shown by the Number of Weeks with Ice multiplied by the Number of Areas with Ice around Iceland: 1831—1940 (after Lauge Koch, 1945).

Decade	Ice Units*	Type	Decade	Ice Units*	Type
1831—40	*56·7*	*Severe*	1901—10	17·1	Moderate
—50	*0·9*	*Light*	—20	20·7	Moderate
—60	35·3	Moderate	—30	*1·2*	*Light*
—70	*59·7*	*Severe*	—40	*1·8*	*Light*
—80	26·5	Moderate			
—90	*69·4*	*Severe*			
—00	30·9	Moderate	Average	29·1	

* See Table I.

severe ice and two successive decades with light ice conditions (1921—1930, 1931—1940). Thus the data afford a wide range of ice conditions for analysis.

2. Temperature.

Annual temperature records for various localities in the Arctic or sub-Arctic are available as far back as 1846 in Iceland (Stykkisholm), as 1840 in Norway (Vardø¹)) and as 1831 for Archangel²). Uninterrupted temperature series from other stations in northern Europe (north of 55°N.) go back even further (i.e., Stockholm, to 1757; Edinburgh, to 1764; Copenhagen, to 1798; Leningrad, to 1806). In North America, on the other hand, New Haven, Connecticut (41°18′N.) is the most northern station with a record extending as far back as 1780.

3. Localities considered for Study.

Since any long-period variations which show a correlation between ice off Iceland and temperatures in that and adjacent areas should be more obvious at stations within or near the Arctic, the situation is first examined at Stykkisholm (Iceland) and then compared with the record from Archangel followed by that for Vardø (Norway) and other localities in northern Europe and the United States.

The location of Archangel on the White Sea suggests that the temperature there is perhaps correlated with ice conditions in the Barents Sea. Unfortunately, ice data for the Barents Sea are not available prior to 1895. We may assume, however, that the mean decadal character of the ice off Iceland (Table II) is indicative in general of ice conditions for the same periods in the Barents Sea³). The long period changes appear similar in the two areas. Thus, the ice retreated northward in the 20's and 30's from both Iceland and the Barents Sea (as well as from the intervening area). Hence, comparison of the Archangel temperature with ice conditions off Iceland appears permissible.

At Vardø on the north coast of Norway, one might expect to find a relation between the temperature there and ice off Iceland similar to that at Archangel. On the other hand, although it is farther north than either Archangel or Stykkisholm, Vardø appears not as affected

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¹) Because there appears to be some doubt as to whether the earliest observations from Vardø (see below) are representative, the data for this station prior to 1868 should be treated with reservation.

²) After the completion of this report it was discovered that the temperature record at Archangel actually started in 1814 rather than in 1831, as listed in the Köppen-Geiger Handbuch der Klimatologie (1939). However, since the ice severity for the decade 1821—1830 was not extreme and since extreme ice conditions will be mainly dealt with here, the earlier temperatures have not been analysed in this report.

³) Beginning with 1895 the general ice pattern in the Barents Sea was generally severe until 1918. From then on to 1939 (last consecutive year available) it was light, or much the same as ice conditions off Iceland for the same periods. During the severe ice period (1895—1918) the mean annual temperature at Archangel and Stykkisholm were, respectively, 0·15°C. and 4·02°C. as compared with 1·53°C. and 4·92°C. respectively during the light ice period (1919—1939) which would corroborate the interdependence of the two areas for longer-period variations in ice.

by northerly winds as the other two (Shaw, 1936). Consequently, it might also be expected to show a somewhat different relation to the ice off Iceland and in the Barents Sea.

The relationship between the general character of the ice off Iceland and the mean decadal temperature at Stykkisholm, Archangel, and to a lesser extent Vardø, is, it was noted above, part of a more extensive system involving the circulation of the North Atlantic as a whole, the areas which border it, and possibly other regions as well.

Because there are no long series of data from the ocean areas in question, in order to show a relation between ice in the North Atlantic—Arctic and the circulation of that general area, it is necessary to use the comparatively long temperature records for areas bordering on the North Atlantic (i.e., northern Europe and the north-eastern part of the United States). The temperatures of these areas are noticeably influenced by the continental air masses. Nevertheless, if one could find a correlation between ice conditions off Iceland and temperatures at these localities, it would support earlier, more limited evidence that variations in the ice of the North Atlantic—Arctic are related to changes in the circulation over very large areas rather than over local ones.

G. Ice Conditions and Temperatures, 1831—1940.

Ice conditions (a) existing at the same decade, (b) in the preceding decade, or (c) in the subsequent one have been compared with air temperatures in the analysis of data (Tables III and IV) for the several localities under consideration here.

1. Stykkisholm.

(a) **Comparison with ice conditions in the same period.** For each of three decades with light ice (1841—1850, 1921—1930, 1931—1940), the mean annual temperature at Stykkisholm for the same period was above average (0·43°C.[1]), 0·65°C., 1·09°C., respectively), the highest positive deviation occurring for the decade 1931—1940 (Table III). On the contrary, for two decades with severe ice (1861—1870, 1881—1890), negative temperature deviations (—0·58°C., —0·53°C.) prevailed at Stykkisholm. These are likewise the lowest on record.

(b) **Comparison with ice conditions of the previous decade.** The decades (1871—1880, 1891—1900) with temperature deviations (—0·13°C., —0·12°C.) somewhat below average, follow decades (1861—70, 1881—90) with severe ice but a third (1841—1850) had a temperature deviation (0·43°C.) above average following a decade (1831—40) with severe ice. However, the latter (1841—50) was a period with little ice. It is significant that though the temperature deviation for the decade as a whole was in all probability positive, it is equally probable that it was markedly less than for other decades with light ice (1921—30, 1931—40) which followed periods of moderate or light ice (Table III). Thus, the latter (1931—1940), following a decade with light ice conditions, had the largest positive temperature deviation (1·09°C.). The decade (1851—1860), on the other hand, which also followed one with light ice, had a small negative temperature deviation (—0·22°C.). This on closer examination appears to have been due to two extremely cold years (1859 and 1860). Thus, for the first eight years (1851—1858) the mean temperature deviation is slightly positive (0·11°C.).

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[1]) Based on 1846—1850 only. However, the entire period of light ice from 1841 to 1854 was implied by Thoroddsen (Meinardus, 1906, p. 155) to have been rather mild in Iceland. According to evidence cited by Jensen (1939) the 1840's must have been quite mild also off the south-west coast of Greenland.

Table III. Mean Annual Temperature Deviation from Long-Term Average at Stykkisholm, Vardø, and Archangel and the Severity of Ice off Iceland, by Decade, during 1831—1940.

Decade	Ice Severity (see Table II)	Stykkisholm °C. Δ	Archangel °C. Δ	Vardø °C. Δ
1831—40	*Severe*	—	— ·47†	—
—50	*Light*	·43*	·35	(— ·20)
—60	Moderate	— ·22	·18	(— ·16)
—70	*Severe*	— ·58	— ·36	(— ·42)
—80	Moderate	— ·13	— ·71	— ·25
—90	*Severe*	— ·53	— ·30	— ·17
—1900	Moderate	— ·12	— ·68	— ·29
—10	Moderate	— ·12	·01	— ·03
—20	Moderate	— ·20	— ·11	·00
—30	*Light*	·65	·65	·53
—40	*Light*	1·09	1·41	·97

* 1846—50. ( ) Approximate value. † 1832 lacking.

(c) **Comparison with ice conditions in a subsequent decade.** Two decades (1861—70, 1881—90) with extreme negative deviations in temperature at Stykkisholm were each followed by moderate, not severe, ice conditions off Iceland (Table III). On the other hand, following decades with a marked positive temperature deviation (1841—50; 1921—30; 1931—40), the ice conditions were moderate in two decades (1851—60; 1941—50[1])) and light in the other (1931—40).

From the foregoing, it is obvious (1) that the decadal temperatures at Stykkisholm reflect ice conditions off Iceland for the same period. Furthermore, it appears (2) that after a decade of severe ice off Iceland, the next decade in the general area of Iceland has temperatures below the average unless it be one with little ice. Similarly, in a decade following one with light ice, the temperature is above average[2]).

(3) Finally, as might be expected, no relationship between the air

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[1]) According to preliminary reports, see p. 29.

[2]) The character of the ice during 1941—1950 is available only in terms, "close to normal", "above" and "below". This and other considerations made it desirable to treat the results for this period separately. Hence, for the temperatures above average following the light-ice decade of 1931—1940, see p. 29.

temperatures of Iceland and ice conditions which occur there at a later date was found, because as mentioned above, the ice off Iceland is chiefly carried down from the north and is not of local origin.

2. Archangel.

(a) **Comparison with ice conditions in the same period.** The temperature deviations for Archangel are positive (0·35°C., 0·65°C., and 1·41°C.) for three decades (1841—50, 1921—30, 1931—40) with light ice. The highest temperature occurred in the third which followed a decade with light ice (Table III). As at Stykkisholm, on the other hand, the temperature at Archangel for the two decades (1861—70, 1881—90) with severe ice as well as for the first decade (1831—40) was below average, deviations being —0·47°C., —0·36°C. and —0·30°C. respectively. These deviations are, however, smaller than those at Stykkisholm. This is the more significant because the standard deviation, σ, of the mean annual temperature at Archangel, ±1·22°C. (1831—1940) is appreciably greater than at Stykkisholm ±0·94°C. (1846—1940).

(b) **Comparison with ice conditions of the previous decade.** Two decades (1871—80, 1891—1900) following decades (1861—70, 1881—90) of severe ice off Iceland, had temperatures (—0·71°C. and —0·68°C.) below average but a third (1841—50) which was free of ice, following one (1831—40) of severe ice had a small positive deviation (0·35°C.). The positive temperature deviation for this decade, however, is much less than those for two other decades with light ice (Table III). Hence, one may assume that had this period (1841—1850) not been almost entirely free of ice, the temperature would likewise have been below average. One decade (1851—1860), on the other hand, following one (1841—1850) of light ice had a slight positive temperature deviation (0·18°C.), but another (1931—1940[1]) had a greater one (1·41°C.), the largest such value recorded (Table III). This in part was probably due to the absence of ice during the period 1931—40.

(c) **Comparison with ice conditions in a subsequent decade.** The three coldest decades at Archangel (1831—40, 1871—80, 1891—1900) were followed by one (1841—50) of light ice, by one (1881—90) of severe ice and by one (1901—10) of moderate ice. Likewise, no consistent relation can be traced between decades with relatively high temperatures at Archangel and ice in subsequent periods off Iceland. Thus, two decades (1841—50, 1931—40[2]) were followed by moderate ice, and a third (1921—30) by light ice.

In short, ice conditions off Iceland are related to temperatures at Archangel for the same period or in the next decade in about the same way as at Stykkisholm, but there is no apparent relationship between temperatures there and ice conditions off Iceland in the next decade.

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[1] For a discussion of temperatures following the decade 1931—1940, see p. 29.

[2] According to preliminary reports (p. 29).

3. Vardø.

(a) **Comparison with ice conditions in the same period.** The Vardø temperature deviations for decades of severe ice (1861—70, 1881—90) are — 0·42°C. and —0·17°C. respectively. Similarly, for three decades with light ice (1841—50, 1921—30, 1931—40), the deviations were —0·20°C., 0·53°C., 0·97°C. respectively (Table III). Thus, only the temperature of the decade (1841—50) does not reflect the ice conditions. Since some of the early Vardø observations are apparently approximations it appears that the Vardø values are relatively consistent with the ice for the general area off Iceland and presumably the Barents Sea.

(b) **Comparison with ice conditions of the previous decade.** Omitting the early Vardø observations, the temperature deviations for the decades (1871—80 and 1891—1900) are both negative (—0·25°C. and —0·29°C. respectively). Both periods followed decades of severe ice. On the contrary, the deviation in the decade (1931—40[1])) which followed a light-ice decade, was positive (0·97°C.). The large deviation in all probability was due to light ice conditions during that period[1]).

(c) **Comparison with ice conditions in a subsequent decade.** Following the two decades (1861—70 and 1891—1900) with the lowest temperatures at Vardø, ice was moderate. On the contrary, following the two with the highest temperatures (1921—30, 1931—40), the ice was light in one (1931—40) and moderate in the other (1941—50[2])).

From the above it appears that the temperatures at Vardø as at Archangel show no consistent relationships to the ice conditions off Iceland the next decade, as was to be expected.

4. Northern Europe (exclusive of Archangel and Vardö) and North-Eastern United States (New Haven, Connecticut).

(a) **Comparison with ice conditions in the same period.** Three decades of severe ice were accompanied by negative temperature deviations in northern Europe as a whole exclusive of Vardø and Archangel, but only the first two (1831—40, 1861—70) had values markedly below the average (—0·41°C. and —0·42°C. respectively) (Table IV). In contrast, two of the three decades (1921—30, 1931—40) of light ice had temperatures above average. For the latter the positive deviation was very marked (0·98°C.).

At New Haven, Connecticut, the temperature deviations (Table IV) were appreciably below the average (—0·83°C., —0·33°C. and —0·41°C. respectively) during each of three decades with severe ice (1831—40, 1861—70, 1881—90) and markedly above the average (0·59°C., 1·18°C.) during two light-ice decades (1921—30, 1931—40) but not during a third (1841—50) (—0·04°C.).

(b) **Comparison with ice conditions in the previous decade.** The temperature deviation of northern Europe following two decades (1831—40, 1861—70) of severe ice were both negative (—0·25°C., —0·35°C.)

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[1]) For the positive temperature deviation following the light-ice decade (1931—1940), see p. 29.

[2]) According to preliminary accounts (p. 29).

Table IV. Mean Annual Temperature Deviation from Long-Term Average in Northern Europe (exclusive of Archangel and Vardø) and North-Eastern U.S.A. by Decade and the Severity of Ice off Iceland during 1831—1940.

Decade	Ice Severity †	Bergen °C. Δ	Edinburgh °C. Δ	Oslo °C. Δ	Stockholm °C. Δ	Copenhagen °C. Δ	Helsinki °C. Δ	Leningrad °C. Δ	Moscow °C. Δ	Northern European °C. Δ	North-eastern U.S.A. (New Haven, Conn.) °C. Δ
1831—40	*S*	—·05	—·27	—·51	—·43	—·53	—·31	—·84	—·35	—·41	—·83
—50	*L*	—·02	·01	—·60	—·25	—·39	—·29	—·24	—·20	—·25	—·04
—60	M	—·02	—·02	—·36	·11	—·28	—·25	—·02	—·15*	—·12	—·48
—70	*S*	—·16	—·17	—·38	—·57	—·33	—·64	—·47	—·66	—·42	—·33
—80	M	—·19	—·28	—·29	—·42	—·25	—·42	—·53	—·41	—·35	·35
—90	*S*	—·14	—·26	·00	—·12	—·19	—·02	·07	—·05	—·09	—·41
—00	M	—·15	·23	·19	·23	·18	—·05	—·11	—·13	0·5	—·06
1901—10	M	—·01	—·07	·30	·02	·06	·19	·24	·21	·12	—·05
—20	M	·00	·09	·41	·22	·40	·26	·29	·19	·23	·38
—30	*L*	·09	·10	·20	·16	·28	·34	·33	·38	·24	·59
—40	*L*	·65	·59	1·09	1·03	·93	1·24	1·14	1·17	·98	·86

† S = Severe, M = Moderate, L = Light. * Based on 9 years only.

but it was somewhat positive (0·05°C.) during a decade (1891—1900) after one (1881—90) of severe ice (Table IV). Following one decade (1841—50) of light ice there was one with a negative temperature deviation (—0·12°C.) but another (1921—30) was followed by one with a positive temperature deviation (0·98°C.[1])).

Likewise, no consistent relation appears between the temperature of New Haven and the ice of the period preceding it. Thus, for the decades (1841—50, 1891—1900) which followed decades of severe ice, the temperature deviations (Table IV) were negative (—0·04°C. and —0·06°C. respectively), but for a third (1871—80), it was positive (0·35°C.). Similarly, one decade (1841—50) of light ice was followed by a negative deviation (—0·48°C.) at New Haven, but a second (1921—30) by a positive deviation (0·86°C.).

(c) **Comparison with ice conditions in a subsequent decade.** For northern Europe, a cold decade (1831—40) was followed by light ice off Iceland, a second (1861—70) by moderate ice there, and a third somewhat less cold decade (1871—80) by severe ice (Table IV). Similarly, at New Haven, Connecticut, a cold decade (1831—40) was followed by light ice, a second (1851—60) by severe ice, and a third (1881—90), which was somewhat less cold, by moderate ice. Again, the warmest decade (1931—40) of all, both in northern Europe and at New Haven, is apparently followed by one with moderate ice (p. 29).

From the comparisons presented above, it appears that temperatures along the north-western and north-eastern borders of the North Atlantic are to some extent related to variations in the ice conditions occurring at the same time off Iceland. One might also expect an ice-temperature correlation between a given temperature trend and ice conditions at some subsequent time, because of the time which must elapse before changes in the circulation of the North Atlantic produce any obvious effects on ice conditions to the north. However, this does not appear to be true since the mean temperature for one decade in northern Europe and the north-eastern United States appears to have no consistent relationship with the ice of the next. This was actually to be anticipated because the temperature variations of these land masses are markedly determined by the air masses over these continents, especially in winter with the development of the Sibirian and North American Highs, rather than by the waters off their shores.

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[1]) For the positive temperature deviations following the light-ice decade (1931—1940) see p. 29.

The absence of a consistent relation for northern Europe, other than at Archangel and Vardø, between decadal ice conditions off Iceland and the mean decadal temperatures in the next decade does not imply that such a relationship does not exist for shorter time intervals. Thus, following severe ice conditions between April and July in the Greenland Sea, the mean North Atlantic cyclonic track (Wiese, loc. cit.), the pressure distribution over north-western Europe (Brooks and Quennell, loc. cit.), and precipitation over the same area (Schell, 1947) in subsequent months all appear to vary with severe- and light-ice conditions.

H. Effect of Ice off Iceland on the Subsequent Temperature at Archangel.

From the examination of the mean decadal character of the ice and corresponding temperature deviations above, it appears that following severe ice, the temperature deviations at Stykkisholm and Archangel tend to be negative and following light ice, positive. With severe ice conditions, for example, off Iceland and a greater flow of water from the Arctic, more cold water can be expected to mix with the warm North Atlantic water moving north-eastward as the Norwegian Current to the Barents Sea and northward to Spitsbergen (Fig. 1[1]).

Farther south, either a southward displacement[2] of the warm North Atlantic water mass (le Danois, 1934) or a contraction of the warm North Atlantic cell, presumably due to the strengthening of the trade wind circulation (Iselin, 1940), results in a southward displacement of the Arctic convergence zone and in a reduced flow of warm water from the south-west. Coincident with the decreased flow of warm water into the Arctic, less warm air would be transported north-eastward.

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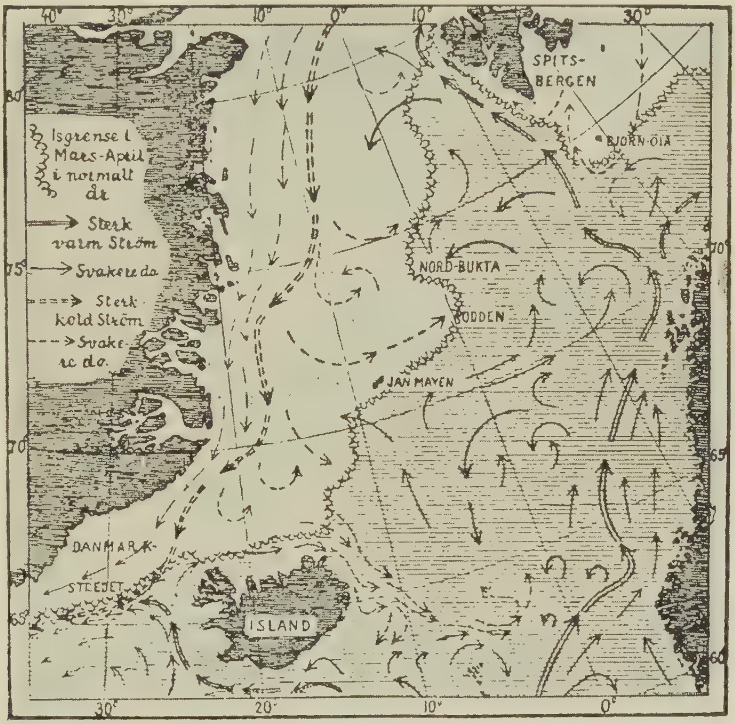
[1] Information obtained since the publication of Nansen's paper confirms the basic picture drawn by him (Kiilerich, 1945).

[2] The word "displacement" seems to the writer a better term for le Danois's "transgression" in describing the horizontal swayings of the large mass of warm North Atlantic water.

In addition, because some time must elapse before the effect of severe ice conditions off Iceland, a stronger East Icelandic Polar Current, etc., can be felt in the general Barents Sea area, the negative temperature deviation at Archangel which arises from the persistence effect of severe ice locally may be expected to be accentuated. Hence, following extreme ice conditions the temperature deviation at Archangel may be expected to be greater than at Stykkisholm where it depends on local persistence of such conditions only and also greater following than during these periods of extreme ice conditions.


40°
30°
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BERGEN
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80
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Svakere do.
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kold Strøm
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re do.
75
70
NORD-BUKTA
ODDEN
JAN MAYEN
70
65
DANMARK-
STREDET
ISLAND
65
60
30°
20°
10°
0°

Fig. 1. Map showing currents and ice conditions in the North Atlantic. After Fridtjof Nansen 1924.

Thus, for the two decades (1871—80; 1891—1900) each following one with severe ice, the negative temperature deviation in each (Table V) was (1) greater at Archangel than at Stykkisholm (—0·58°C. v. —0·13°C. and —0·68°C. v. — 0·12°C. respectively) and (2) greater at Archangel in the succeeding decade than during the one (—0·58°C. v. —0·36°C. and —0·68°C. v. — 0·30°C., respectively) of the severe ice.

For a decade (1841—50) of light ice with a positive temperature deviation (smaller than during the other two light decades presumably in response to the decade of severe ice before (1831—40)), the positive deviation was smaller at Archangel than at Stykkisholm (0·35°C. v.

0·43°C.). This suggests that cold water and ice at Iceland the previous decade (1831—40) may have affected conditions at Archangel the succeeding one (1841—50).

The decade of moderate ice (1851—60) following another with light ice (1841—50) showed a positive temperature deviation at Archangel as compared with a negative one at Stykkisholm (0·18°C. v. —0·22°C.). The Archangel temperature, however, was not higher than that for the previous decade[1]). The temperature deviation at Archangel for 1931—40, following the light-ice decade (1921—30) was somewhat greater than at Stykkisholm even allowing for Archangel's larger standard deviation, σ, (1·41°C. v. 1·09°C.) and was also greater than for the previous decade (1·41°C. v. 0·65°C.). It is not possible to make any definite conclusions about the effect of light ice off Iceland for 1931—40 on the Archangel temperature in the years 1941—50, because only one year (1949) of the Archangel record is available. Furthermore, the decade (1931—40) itself was one of little ice. The Archangel deviation that year was positive and one of the largest (2·3°C.) on record.

Table V. Differences in Temperature Deviations between Archangel and Stykkisholm for Decades following Severe and Light Ice, respectively, off Iceland: 1831—1950.

Decade		Ice Character		Archangel °C. Δ	Stykkisholm °C. Δ	Difference °C. Δ
Contemporary	Following					
1831—40		Severe		— ·47	—	
	1841—50		Light	·35	·43	— ·08
1861—70		Severe		— ·36	— ·58	
	1871—80		Moderate	— ·58	— ·13	— ·45
1881—90		Severe		— ·30	— ·53	
	1891—00		Moderate	— ·68	— ·12	— 56
1841—50		Light		·35	·43	
	1851—60		Moderate	·18	— ·22	·40
1921—30		Light		·65	·65	
	1931—40		Light	1·41	1·09	·32
1931—40		Light		1·41	1·09	
	1941—50		Moderate	2·3*	1·14	

* 1949 only.

On the whole, following severe and light ice respectively, off Iceland, the temperature at Archangel is more extreme than at Stykkisholm since it not only reflects conditions in that general area but also seems accentuated by a stronger or weaker East Icelandic Current diluting the warm North Atlantic water entering the Barents Sea. This is a Dynamic Persistence relationship. The temperature trend at Archangel is related to the preceding conditions in the general area off Iceland through the persistence of these conditions and a translation of their effect north-eastward.

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[1]) The circulation associated with the light-ice decade (1841—50) was probably not as intense as during the recent light-ice period (1919—1940) when all of northern Europe as well as north-eastern United States had the highest temperatures on record. This may explain the rather small positive temperature deviation at Archangel the next decade (1851—60) and negative deviation at Stykkisholm. (For the first eight years (1851—58) it was positive, averaging 0·11°C.).

I. Ice and Temperature Trends: 1941—1950 and after.

The light ice off Iceland during the last two decades (1921—40) raises the question as to whether the mean temperature during the present one (1941—50) in the general vicinity of Iceland, Vardø, and Archangel will prove to be above average and also as to whether the positive deviation at Archangel will be greater than at Stykkisholm as suggested above. Actually, since there were two consecutive decades with light ice we might expect to find especially large positive temperature deviations at Stykkisholm for 1941—50 provided the ice trend during this decade has not reversed itself.

Rough estimates of the ice conditions off Iceland for the period 1941—50 (U.S. Coast Guard Bull. 1947; Dansk Meteorologisk Institut; author's correspondence) indicate the following:—

1941	"close to normal"
1942	"below normal"
1943	"somewhat above normal"
1944	"much above normal"
1945	"close to normal"
1946	"close to normal"
1947	"somewhat less than normal"
1948	"close to normal"
1949	"much above normal"
1950	"somewhat less than normal"

or, taking the ten years together the ice off Iceland for 1941—50 may be considered as "close to normal".

Hence, since the ice as a whole was not severe enough to counteract a trend toward temperatures above normal influenced by the presence of little ice in the two preceding decades, we may assume that the mean temperature for 1941—50 was to be above average at Stykkisholm, at Archangel, and perhaps also at Vardø.

Observations at Stykkisholm indicate that the mean annual temperature for the period 1941—50 corresponding to on the whole normal ice conditions off Iceland was 1·14°C. above average compared with 1·09°C. in the preceding decade (1931—40). The mean annual temperature at Archangel for the year 1949 was one of the highest on record. At Vardø¹) the average temperature deviation based on eight years (1941—3, 1946—50) was 0·47°C.²).

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¹) The station was destroyed in August 1944 and did not open again until June 1945. Comparison with neighbouring stations, however, indicated that the annual temperature in 1944 and 1945 was slightly above normal.

²) The mean 1941—50 annual temperature deviation at Edinburgh was 0·55°C., at Bergen 0·56°C., at Oslo 0·91°C., at Stockholm 0·74°C., at Helsinki 0.68°C., at Copenhagen 0·80°C., and at New Haven, Connecticut, 1·50°C. (Table VI).

Table VI. Average Annual Temperatures at Archangel, Bergen, Copenhagen, Edinburgh, Helsinki, Leningrad, Moscow, New Haven (Conn.), Oslo, Stockholm, Stykkisholm, and Vardø for the Period 1831—1940 and Decade 1941—50 (except as noted).

Year	Archangel	Bergen	Copenhagen	Edinburgh	Helsinki	Leningrad	Moscow	New Haven	Oslo	Stockholm	Stykkisholm	Vardø
	°C.	°C.	°C.	°F. 40 †	°C.	°C.	°C.	°F. 40 †	°C.	°C.	°C.	°C
1831—1940	0·41°	7·22	7·66	7·26	4·22	4·01	4·22†	9·37	5·72	5·78	4·15*	0·93°°
1941—1950	—	7·78	8·46	8·19	4·90	—	—	12·08	6·63	6·62	5·28	1·40**

° Except 1832. † Except 1859. * 1846—1940. °° 1841—1940. ** Mean 1941—43, 1946—50.

Comparing the ice off Iceland for the period (1941—50) with that of the preceding 22 years (Table I), it appears that while in the 10-year period (1941—50) the ice was on the whole "close to normal" and in at least two years, "above normal", in each year of the period 1919—40 the ice was "below normal". Fourteen years had no ice at all. The trend, therefore, for very little ice may not have reversed itself, but, at least, it has temporarily ceased.

If the general atmospheric circulation is self-contained, any prolonged rise in the temperature in high latitudes will weaken the general atmospheric south-north temperature gradient. As a result, the transport of warm air poleward will soon decrease and conditions favouring an increase in the polar ice-cap and a greater flow of ice into the East Greenland Polar Current and also towards Iceland will occur once more (Schell, 1940).

We may, therefore, expect from the relationship described above and from the evidence for the period 1941—50, suggesting that the trend of light ice has ceased, that everything else being constant, the trend toward high temperatures in the general vicinity of Iceland, Vardø, and Archangel is not likely to continue long in its present intensity. The change at Archangel, however, would be expected to occur later than at Stykkisholm.

J. Summary.

1. We have assumed that due to the interaction between air and the oceans the trend of ice off Iceland and that general vicinity must be closely related to the circulation in the northern North Atlantic and adjacent areas. In addition, because of local or simple persistence of the ice and the polar water associated with it, a relationship was also assumed between ice of the North Atlantic—Arctic and the circulation trends for the next decade in the area of the ice and general vicinity. Finally, because the effect of simple persistence in the ice etc. may be

also translated to distant areas with which the ice area is linked synoptically, a relationship was assumed between the ice etc. off Iceland and the following conditions to the north-east, in accordance with the general circulation pattern of that region.

2. In this investigation, only the air temperatures of Iceland, northern Europe, and the north-eastern United States (1831—1950) were compared with ice conditions off Iceland. A consideration of direct measures of air and water circulation to be derived from ocean currents, pressure distribution, winds, etc. is planned for the future. The analysis was also limited to prolonged periods of severe- and light-ice conditions to permit the relationships between ice and temperature to become more obvious than is possible in comparing "close to normal" conditions. Under the latter circumstances, fluctuations in the temperature can occur in either direction[1]) because of the quasi-stable character of the circulation.

3. Comparison of the mean decadal ice extremes with mean temperatures for the same decades at Stykkisholm, Archangel, and Vardø indicates a definite relationship between the two for the same period (Table III). Thus, three decades with severe ice off Iceland (1831—40, 1861—70, 1881—90) were accompanied by temperatures below average at Archangel. At Stykkisholm and Vardø, where no data are available for a decade with severe ice (1831—40), temperatures were below average in the other two decades in question. Similarly, three decades with light ice (1841—50, 1921—30, 1931—40) were accompanied by temperatures above average except at Vardø in the one decade (1841—50), (see below). Comparison of the mean decadal temperature of northern Europe, exclusive of Archangel and Vardø, and of the north-eastern United States with the ice off Iceland indicates that the circulation over these areas is to a marked degree part of the same process that determines ice conditions of Iceland (Table IV).

4. Furthermore, the temperatures of Iceland, Archangel, and perhaps also Vardø[2]) are seemingly related to the ice conditions of the previous decade. This apparently means that the effects of ice and cold water persist for a considerable period locally. Thus, lower than average temperatures usually follow decades with heavy ice, and higher

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[1]) Actually, at Stykkisholm, which unlike Archangel, appears to be uncomplicated by an accentuation of effects caused by a transport of water from the west, the temperature deviation also corresponded to the ice character for the moderate ice decades.

[2]) From the fact that Vardø lies between Iceland and Archangel and appears more exposed to the influence of the warm North Atlantic water flowing around the North Cape than Archangel, we might have expected better agreement between the Vardø temperatures and the ice conditions of the previous decade than was actually obtained. We have already noted the possibility that some of the Vardø observations during the early period of that station's operation are only approximate. It is also possible in view of Vardø lying to the west of Archangel that the effect of different ice extremes off Iceland on Vardø's temperature occurs earlier there than at Archangel and for that reason the relation of the Vardø temperature with the ice may not have been as clear in the decadal comparison.

temperatures, decades with light ice. In addition, these are presumably strengthened at Archangel by cold water carried south-eastward from Iceland and mixed with the north-eastward flowing warm North Atlantic water on the principle of Dynamic Persistence. Hence, at Stykkisholm the extreme deviations occur during periods of extreme ice conditions (Table III), but at Archangel, the extreme deviations occur in the decade following one of extreme ice conditions.

5. No consistent relationship was indicated between the ice off Iceland and the temperature of Iceland, Archangel, Vardø, etc. during the preceding decade.

6. The reversal in trend from practically no ice at all during the period from 1919 to 1940 toward on the whole normal conditions for the period 1941—50 suggests that the trend toward comparatively high temperatures in the general areas of Iceland, Vardø, and Archangel is not likely to continue much longer. The change at Archangel would, however, occur later than at Stykkisholm.

7. The explanation of the decadal temperature trend at Iceland and Archangel in terms of the preceding circulation as reflected in the ice off Iceland rather than in terms of the sunspot number[1]) suggests that while solar changes may be the basic cause of the variations in the general circulation, they cannot be readily discerned in the temperature fluctuations examined here.

K. Appendix.

1. Influence of City Development on the Temperature.

In connexion with the increase of the temperature in recent decades at stations considered here, the question arises as to what extent the rise at stations in cities has been due to the growth of the city itself. A recent comparison (Liljequist, 1943) of the mean December—March temperature in Stockholm and with a station "2·5 km. north of the observatory of Stockholm and about 1·5 km. outside Stockholm proper" for the period 1882—1940 shows that the observatory values have always been slightly higher, but there has been no consistent increase in the temperature difference between the two locations. Similarly a comparison of the annual temperatures in Copenhagen with those of a neighbouring village for the period 1861—1935 indicates that the effect of upbuilding is only about 0·15°C. (Lysgaard, 1937). Essentially the same conclusions have been drawn for other areas, such as the United States (Kincer, 1933, 1946), and the East Indies (de Boer and Euwe, 1949). From these reports we may safely conclude that by far the major portion of the marked rise in temperatures in recent decades at Oslo, Leningrad, Moscow, etc. was due to the same causes that produced the rise at Stykkisholm where the question of city upbuilding does not arise.

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[1]) The average sunspot number for the 3 light-ice decades was 57, 42, and 54 respectively, and for the 3 severe-ice decades, 66, 53, and 35 respectively.

2. Temperature Data.

The data were taken for the most part from World Weather Records by H. H. Clayton (Editor) (1927, 1934, 1947) and the Handbuch der Klimatologie by W. Köppen and R. Geiger (1939). The use here of temperature observations over the long period 1831 to 1940 or later made it desirable to examine the data carefully to make sure that the data were comparable. In many cases the site of the stations had changed. Accordingly certain corrections have been necessary for some of the published series.

Archangel.

The mean annual values for 1831—1930 except for the years 1832, 1833, and 1921 are available in the Köppen-Geiger (1939) Handbuch d. Klimatologie (Section N_2) tabulated as deviations from the mean 0·2°C. The values for 1881—1915 were 0·1°C. too high, and from those for 1922—1930, 0·2°C. had to be subtracted, to correct them to the 24-hr. mean.

The data for 1921 were found in Réseau Mondial and an approximate value for 1833 was derived from the figures for the 10-month period March—December and the long-term average for January and February. The new mean derived from the 109-year series, 1831—1940 (less 1832), is 0·41°C. The mean annual value for 1949 was derived from figures in Die Mitteleurop. Grosswetterlage, Deutsch. Wetterdienst, U. S. Zone, Bad Kissingen.

Leningrad.

The values given as deviations from a mean of 3·9°C. for 1831 to 1920 were taken from the Köppen-Geiger (1939) Handbuch d. Klimatologie and those for 1921—1940 from World Weather Records (Clayton (Ed.), 1927, 1934, 1937). The annual values for 1921—30 were reduced by 0·1° to correct them to 24-hr. means. The 1831—1940 mean is 4.01°C.

Moscow.

The temperature values given as deviations from a mean of 3·5°C. at the Konstantin Institute (55°36′N., 37°40′E.) for 1831 to 1930 (except 1859) were taken from the Köppen-Geiger (1939) Handbuch. The values for 1916—1930 represent temperatures from another station, the Agricultural Institute (55°50′N., 37°33′E.), where the mean annual temperature was found to be 0·7°C. lower. Thus, the values from 1916 to 1930 had to be increased by 0·7°C. However, since those for 1921—1930 were not corrected to 24-hr. means, only 0·6°C. was added to the values for that period. Furthermore, the March 1930 temperature was incorrectly given as —12·2° instead of —1·2° (in both the Handbuch and the World Weather Records), the net rise for that year was actually only +1·5°C.

Finally, the values for 1931—40 (World Weather Records, Volume III) had to be increased by 0·7°C. to make them comparable with the corrected series for 1831—1930. The new mean derived from the 109-year series (1831—1940, omitting 1859) is 4·22°C.

Stykkisholm.

Mean annual temperatures for the period 1846—1930 were taken from World Weather Records (Clayton (Ed.), 1927, 1934, 1937) and for all subsequent years were obtained through correspondence. The values are based on observations made at 2 p. m. except for the period January 1869 to May 1873 when the observation was taken at noon. The latter have been adjusted to conform with the 2 p. m. reading by adding 0·4°C., with one exception (1873). For the five months of that year only 0·2°C. was added. The mean based on the 95-year period, 1846—1940, is 4·15°C.

Bergen and Oslo.

The mean annual temperatures up to 1940 were taken from World Weather Records (Clayton (Ed.), 1927, 1934, 1937), and for subsequent years, from official publications and by correspondence. The Oslo station was moved to a new site (Blindern) in May 1937, and the records taken there have been reduced to make them comparable with the series from the old site by adding 0·9°C. to the annual figure. The Bergen and Oslo means for the period 1831—1940 are 7·22°C. and 5·72°C. respectively.

Vardø.

The data for the period from 1867 to 1933 are from Table II (p. 33), those from 1840 to 1866 from Tables Ia and I b (p. 32) in Birkeland's (1934) paper, and those after 1933 from official publications and from personal correspondence. The figures for the period from 1867 to 1875 in Table Ib (Skancke's series) do not differ in a uniform way from those for the same period in Table II. Thus, some of the values for 1856 to 1866 as well as those for some of the earlier years must be regarded as approximations only. The mean value for the 100-year period 1841—1940 is 0·93°C.

Stockholm.

The data given as deviations from the mean 5·7°C. until 1925 were taken from the Köppen-Geiger (1939) Handbuch der Klimatologie and after that were obtained from official publications and by personal correspondence. The 1831—1940 mean is 5·78°C.

Copenhagen.

The information up to 1940 is from World Weather Records (Clayton (Ed.), 1927, 1934, 1937) and for subsequent years by correspondence. The 1831—1940 mean is 7·66°C.

Edinburgh.

The mean annual values from 1831 to 1863 are taken from a paper by Brunt (1925), from 1864 to 1940, from World Weather Records (Clayton (Ed.), 1927, 1934, 1937), and from 1941 on, through personal correspondence. Because of a recent change in the site of the station, 0·6°F. was added to the annual figure to make the values after 1930 comparable with the earlier series with 1931. The mean value for the 110-year period 1831—1940 is 47·26°F.

New Haven, Connecticut.

The data up to 1940 were obtained from World Weather Records (Clayton (Ed.), 1927, 1934, 1937) and subsequently through personal correspondence. After 30. June 1943, temperatures have been taken at the airport station. To reduce the data taken there to a comparable basis with that of the old site, 1·9°F. has been added. For 1943, however, to adjust for the first six months at the old site, only 1·0°F. was added. The mean value for the 110-year period of 1831—1940 is 49·37°F. The value for the year 1897 was erroneously given as 48·7°F. instead of 49·5°F.

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TURBIDITY CURRENTS AND SEDIMENTS IN NORTH ATLANTIC[1]

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ABSTRACT

During the past 4 years a large collection of deep-sea cores from the North Atlantic has been brought together at the Lamont Geological Observatory. These cores show that during Pleistocene and Recent time large quantities of sediment of shallow-water origin have been deposited in the deep basins of the North Atlantic. It is inferred that turbidity currents are responsible for the transportation of this material. The effect of such a depression-filling process upon the regional topography is discussed. The effectiveness of turbidity currents as agents of erosion is considered, and it is concluded that erosion by turbidity currents is sufficient to explain the origin of the Hudson Submarine Canyon. In support of the discussion the paper is followed by a list of some of the most important cores, with short lithologic descriptions.

In 1947 a series of bottom-sediment cores was taken in the North Atlantic by the research vessel *Atlantis* of the Woods Hole Oceanographic Institution. Among these were several cores which contained sediments not at all in accordance with orthodox theories of sedimentation in deep ocean basins. Stimulated by these

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Two cruises of the research vessel *Atlantis* of the Woods Hole Oceanographic Institution in 1947 and 1948, which yielded results of extraordinary interest have led to a long-term study of North Atlantic sediments. The cruises were sponsored by the National Geographic Society, the Woods Hole Oceanographic Institution, and Columbia University (Mid-Atlantic Ridge expeditions). Subsequent coring and investigation of the topography of the Atlantic basin have been supported by contracts with the Office of Naval Research and the Bureau of Ships, United States Navy. The coring operations have never been the principal object of a cruise due to lack of funds for ships' time, but have been planned to utilize all available spare time (which on one occasion amounted to a few days) on cruises made for other purposes.

Study and analysis of the cores have been conducted at the Lamont Geological Observatory with financial support of Columbia University and the Office of Naval Research contract No. Nonr 266(01).

To the Woods Hole Oceanographic Institution and its personnel the writers are particularly grateful. Without the generous cooperation of Columbus O'D. Iselin, former director of the Institution, Adrian K. Lane, master of the *Atlantis*, and many other members of the organization, the material discussed here could not have been obtained.

In the laboratory analysis of the cores the writers have been assisted by Beatrice Allegaert Officer, Lucille Hoffman Edwards, Gösta Wollin, and Janet Wollin. The plates were drafted by Marie Thorp Flanagan and Morris I. Wirship.

The Hvorslev-Stetson coring apparatus used in 1947 was lent by H. C. Stetson. During the 1948 summer cruise this apparatus was modified to use a larger-diameter tube, and a piston was added whose function was to overcome the friction of the core against the walls of the tube according to the principle discussed by Kullenberg (B. Kullenberg, "The Piston Core Sampler," *Svenska Hydrografisk-Biologiska Kommissionens Skrifter*, Tredje Serien, Hydrografi. Band 1, Häfte 2, 1947). The great majority of the cores have been taken by one or more of the writers, who wish to acknowledge valuable assistance from R. S. Edwards, John Northrop, J. L. Worzel, Ivan Tolstoy, Ezra Smith, Gösta Wollin, John Ewing, Monroe Cheney, Jr., George Sutton, and many others.

The writers are indebted to H. G. Richards, of the Philadelphia Academy of Science, for identification of the mollusks from core A-156-12. H. H. Hess, Princeton University, and James T. Fyles, Columbia University, examined the samples of igneous rock from the Challenger Banks.

findings, the writers have taken many more cores on subsequent cruises with the consequence that there is now at the Lamont Geological Observatory a large collection of deep-sea cores. This abundant material from widely scattered areas of the North Atlantic has yielded evidence indicating that transportation of sediment by turbidity currents is a process of the first importance in deep-sea sedimentation.

By means of echo-sounding traverses it has been possible to trace the Hudson Submarine Canyon to a distance greater than 200 miles[5] beyond the edge of the continental shelf and to a depth of more than 4,400 meters (2,400 fathoms).[6] Farther out the slightly entrenched canyon becomes lost on a broad plain gently sloping toward the southeast.

Several cores taken within the canyon on the steep walls have entered a green pyritic clay containing a Mio-Pliocene microfauna. Exposures of the green clay occur here and there along the canyon walls, since in some cores there is no Recent sediment overlying the green clay. At one place the coring tube has entered what is evidently a talus composed of masses and fragments of the green clay. Another core has passed through a confused layer made up of rolled and contorted masses of variously colored clays before entering the green clay.

Cores taken on the flat bottom of the canyon have penetrated sand and even gravel. The gravel, which underlies a thin layer of sand and ooze, is composed of pebbles of various igneous, metamorphic, and hard sedimentary rocks together with rolled masses of green clay and pebbles of an upper Eocene chalk which is known to crop out in the bed of the canyon at the northwest where it cuts deeply into the continental slope. The mollusks and foraminifera contained in the gravel belong to Pleistocene or Recent species and some are typical of shallow water.

A suite of cores taken on the broad plain southeast of the Hudson Canyon, for which the name Hudson Canyon Delta has been used,[7] proves that there has been intermittent deposition of sand over an area of not less than 6,000 sq. mi. (15,500 sq. km.). The sand occurs in layers varying in thickness from mere films to beds several meters thick interbedded with red clays and oozes of abyssal facies. The number of layers varies from core to core. In a long core there may be as many as twenty or more. As a rule there is increase in the number of layers, in their thickness, and in coarseness of particles, with depth in the cores. Lower contacts of the sand layers are everywhere sharply defined. The upper contacts in some places are equally well defined; in others, they are gradational through silt into silty gray clay which in turn passes into abyssal red clay. Particle-size sorting is very good and in some layers there is gradation of particle sizes from coarse at the bottom to fine at the top. The foraminifera of the sands and interbedded clays show that deposition took place in Pleistocene time.

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[5] Throughout this paper "mile" means the nautical or geographical mile equal to 1,853 meters or 6,080 feet.

[6] All depths are obtained from echo soundings, using the standard velocity, 800 fm./sec.

[7] D. B. Ericson, Maurice Ewing, and Bruce C. Heezen, "Deep-Sea Sands and Submarine Canyons," *Bull. Geol. Soc. America*, Vol. 62 (1951), p. 962.

The dominant mineral of the sands is quartz but there is almost everywhere present an important quantity of glauconite, as well as various feldspars, micas, and ferromagnesian minerals. In the coarser sands particles of red and gray shale, limestone, chert, mica schist, and fine-grained sandstone are present. In shape the sand grains show much variation. Although the most of them are angular, there is without exception a small fraction composed of rounded to nearly spherical grains, some of which are frosted. Usually several per cent of the larger grains are stained red.

In most respects the sand corresponds fairly well with the sands of the continental shelf northwest of the Hudson Submarine Canyon as described by Shepard and Cohee.[8] However, similarity between the delta sands and the sediments of the shelf is still better shown by samples taken by Bruce C. Heezen and John Northrop on the shelf near the Hudson Submarine Canyon. In some of these Ericson has found not only the red-stained quartz grains and particles of red and gray shale, characteristic of the delta sands, but also the same species of foraminifera which occur in the delta sands. The only important difference between the sediments of the two environments is in degree of particle-size sorting, the shelf sediments being poorly sorted and all the sands of the delta being well sorted.

During the past 75 years, since the first discovery of deep-sea sands, various theories of origin have been proposed. However, because of inadequate coring devices, thick sand layers beneath even very moderate cover of ooze or clay were not reached by the earlier deep-sea expeditions. With what meager material was then obtainable it was impossible to test fully the various theories of origin. Today the situation has greatly changed. Having before us numerous long cores containing sand taken along traverses specifically planned in order to test the older theories of origin, we are now able to reach some conclusions regarding the origin of these remarkable sediments.

According to one of the older theories, the sands were carried out to sea by violent winds during the ice ages. While we are quite willing to admit the Pleistocene storms were powerful, we think that it is asking a little too much of even a Pleistocene gale to transport the 15-mm. pebbles of the Hudson Canyon gravel a distance of more than 100 miles.

Another, more plausible, theory supposes that the sands and gravel were transported by drifting ice during the Pleistocene. That much coarse clastic sediment has been so transported there can be no doubt. Characteristically glacial marine sediments are without sorting, quite unlike the sands of the cores. However, it is perhaps conceivable that fairly well sorted sand might be transported by ice and that it might come to rest on the bottom as a graded bed, but material so transported would certainly be deposited without regard to bottom topography. We believe that the distribution of the sands and gravel in depressions, that is, in canyons but not on the divides between, and below slopes but not on

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[8] F. P. Shepard and G. V. Cohee, "Continental Shelf Sediments Off the Mid-Atlantic States," *Bull. Geol. Soc. America*, Vol. 47 (1936), pp. 445–50.

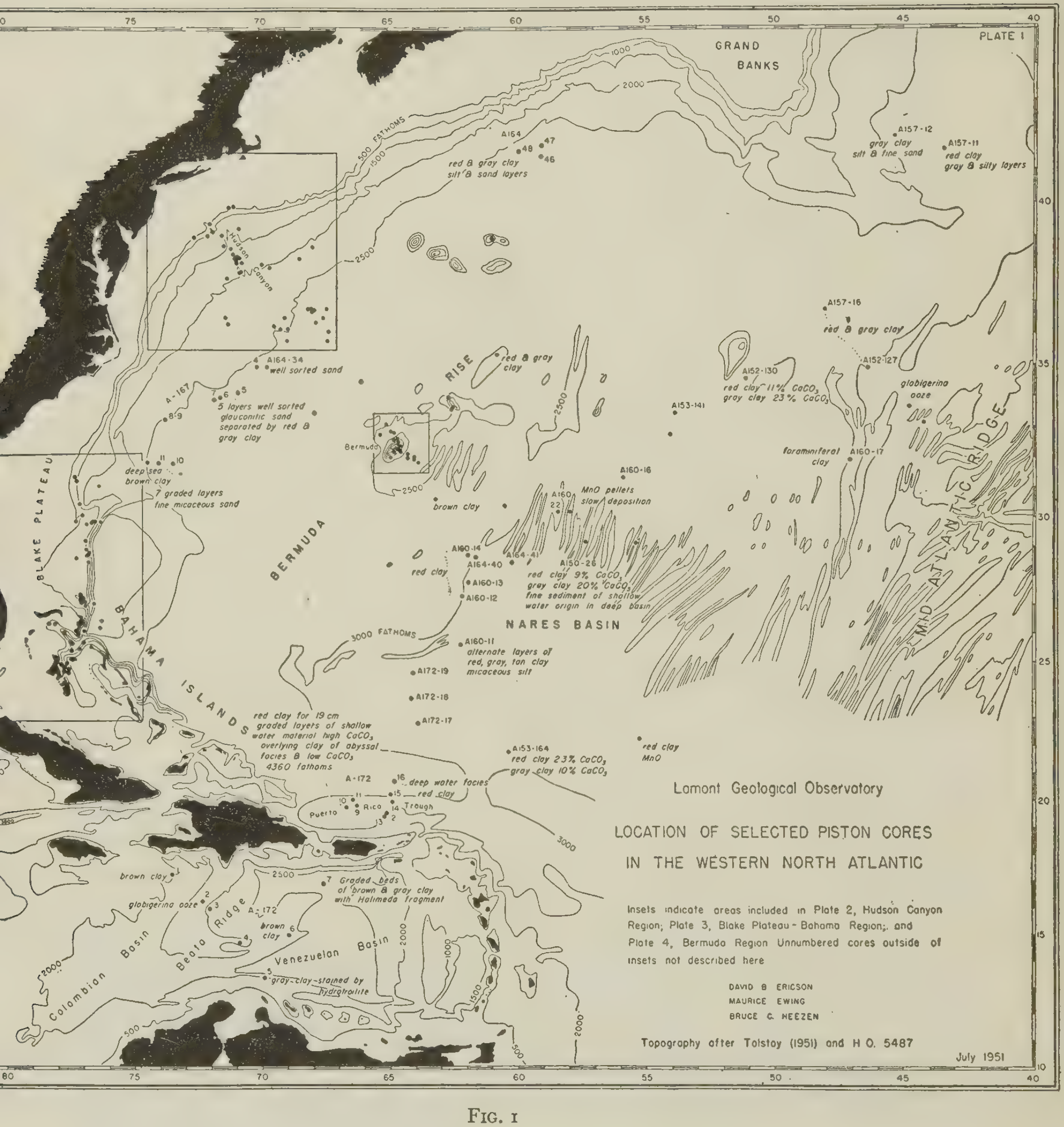
PLATE I
GRAND BANKS
1000
2000
500 FATHOMS
1500
2500
A164 48 47 46
red & gray clay silt & sand layers
A157-12 gray clay silt & fine sand
A157-11 red clay gray & silty layers
Hudson Canyon
A157-16 red & gray clay
A152-127
A152-130 red clay 11% CaCO3 gray clay 23% CaCO3
globigerina ooze
A153-141
A164-34 well sorted sand
A-167 7 6 5 8-9
5 layers well sorted glauconitic sand separated by red & gray clay
RISE
red & gray clay
Bermuda
foraminiferal clay
A160-17
A160-16
BLAKE PLATEAU
11 10 deep sea brown clay
7 graded layers fine micaceous sand
A160 22 MnO pellets slow deposition
brown clay
BERMUDA
MID ATLANTIC RIDGE
A160-14 A164-40 A164-41 A150-26
red clay
A160-13 A160-12
red clay 9% CaCO3 gray clay 20% CaCO3 fine sediment of shallow water origin in deep basin
NARES BASIN
3000 FATHOMS
A160-11 alternate layers of red, gray, tan clay micaceous silt
BAHAMA ISLANDS
A172-19
A172-18
A172-17
red clay for 19 cm graded layers of shallow water material high CaCO3 overlying clay of abyssal facies & low CaCO3 4360 fathoms
A153-164 red clay 23% CaCO3 gray clay 10% CaCO3
red clay MnO
A-172 16 deep water facies
15 red clay
10 11 Puerto 9 Rico 14 Trough 13 2
3000
Lamont Geological Observatory
LOCATION OF SELECTED PISTON CORES IN THE WESTERN NORTH ATLANTIC
Insets indicate areas included in Plate 2, Hudson Canyon Region; Plate 3, Blake Plateau - Bahama Region; and Plate 4, Bermuda Region Unnumbered cores outside of insets not described here
DAVID B ERICSON
MAURICE EWING
BRUCE C. HEEZEN
Topography after Tolstoy (1951) and H O. 5487
July 1951
brown clay 1
2500
7 Graded beds of brown & gray clay with Halimeda fragment
globigerina ooze 2 3
Beata Ridge
A-172
brown clay 6
4
Colombian Basin
Venezuelan Basin
2000
1000
1500
5 gray clay stained by hydrotroilite
500
2000
80 75 70 65 60 55 50 45 40
40 35 30 25 20 15 10

FIG. 1

them, is sufficient evidence to disprove the theory without further discussion.

Any explanation of the sands which involves deposition by subaerial streams at a time of greatly lowered sea-level leads to the embarrassment of having to reduce the North Atlantic to hardly more than a series of isolated puddles. A further difficulty is that the sands are interbedded with clays of abyssal facies. Other evidence fatal to the theory of greatly lowered sea-level is afforded by Core A164-14 taken on the plain or delta at a depth of 4,810 meters (2,630 fms.). The uppermost part of this core is a graded layer of sand 72 cm. thick resting on red clay containing a Recent assemblage of planktonic foraminifera, which in turn rests on red clay containing species of foraminifera characteristic of cold water. The absence of clay of abyssal facies above the sand suggests that the sand was deposited very recently, but it can not be regarded as proof since removal of overlying clay by submarine erosion or slumping must be admitted as a possibility. However, from other cores taken in this part of the North Atlantic we know that the assemblage of planktonic foraminifera now inhabiting the region invaded it rather suddenly in late Wisconsin time. We also know that the thickness of this layer containing Recent foraminifera in cores adjacent to A164-14 is about 38 cm. Since the thickness of the corresponding layer beneath the sand in A164-14 is 38 cm. it is evident that, with due allowance for small differences in the rate of deposition from place to place, the sand must have been deposited at most only a few hundred years ago, and certainly at no time of greatly lowered sea-level.

We have no intention of denying that there have been moderate lowerings of sea-level, that is, by 100 or 200 meters, during the glacial stages of the Pleistocene. Neither do we deny the importance of moderately lower sea-level in the generation of turbidity currents, and consequently in the distribution of deep-sea sands. As Daly has pointed out,[9] turbidity currents should have been particularly frequent at times of lower sea-level when great quantities of mud on the shelf must have been exposed to the churning effect of storm waves. As previously mentioned in this paper, there is in most cores a marked decrease from bottom to top in the number, thickness, and coarseness of sand layers. It is very probable that this is a consequence of rising sea-level in late Wisconsin time.

It has been suggested that these sands may owe their present position to sedimentary vulcanism, that they were originally deposited at some time, presumably long before Pleistocene time, when the configuration of the North Atlantic basin was quite different, and that during the Pleistocene they were forced upward as intrusions into the overlying sediments. Even if it is admitted that sand intrusions might spread along bedding planes, and thus appear to be interbedded with younger sediments, it is hardly conceivable that such sedimentary "sills" could acquire graded bedding. However, it is perhaps possible that dike-like intrusions might erupt on the sea bottom, and that the sand, spreading from the center of eruption, might come to rest as a graded bed. The absence of Mesozoic

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[9] R. A. Daly, "Origin of Submarine Canyons," *Amer. Jour. Sci.*, Vol. 31 (1936), pp. 401–20.

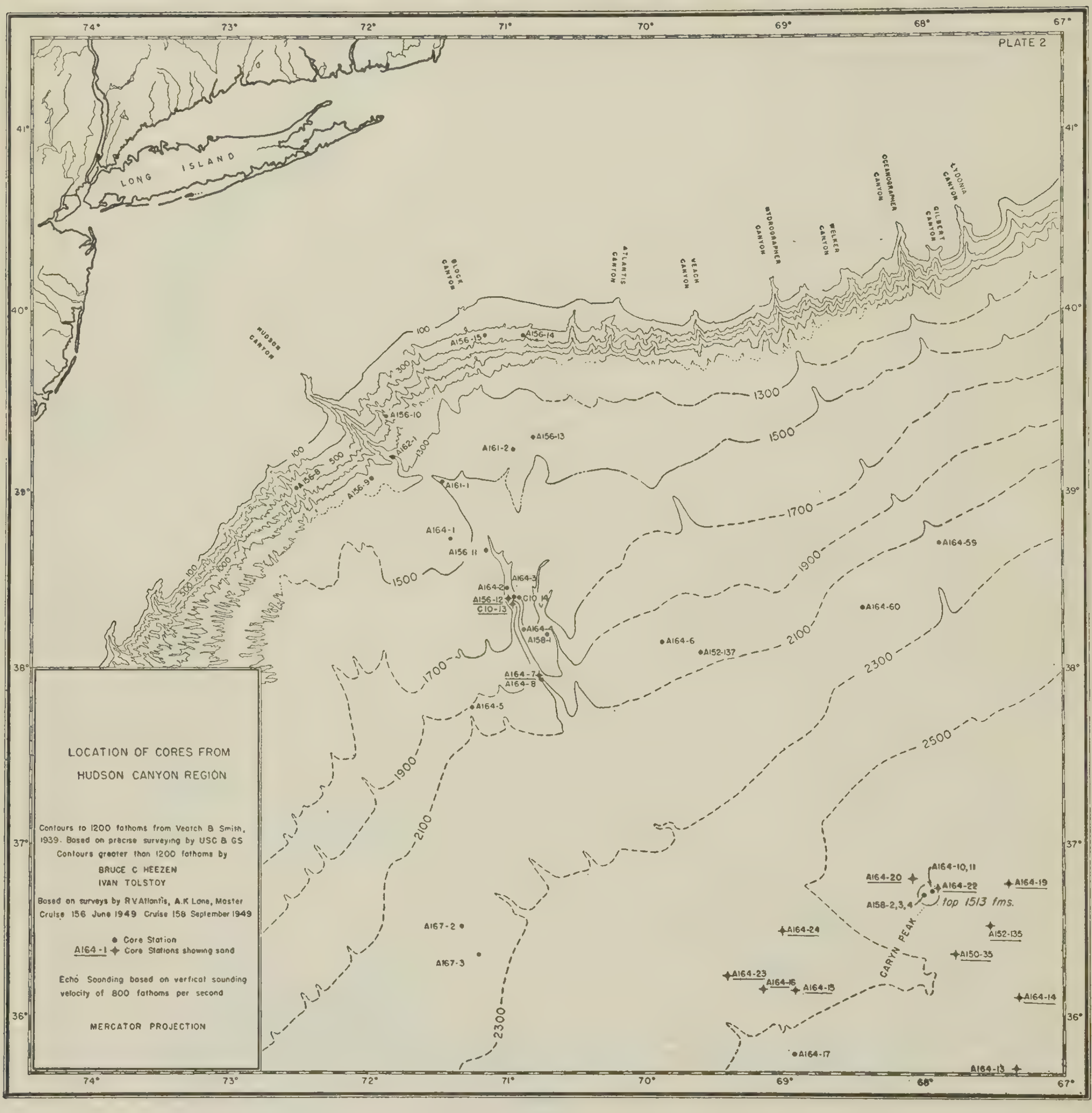
PLATE 2
LOCATION OF CORES FROM
HUDSON CANYON REGION
Contours to 1200 fathoms from Veatch & Smith, 1939. Based on precise surveying by USC & GS
Contours greater than 1200 fathoms by
BRUCE C HEEZEN
IVAN TOLSTOY
Based on surveys by R.V.Atlantis, A.K Lane, Master
Cruise 156 June 1949 Cruise 158 September 1949
● Core Station
A164-1 ✦ Core Stations showing sand
Echo Sounding based on vertical sounding velocity of 800 fathoms per second
MERCATOR PROJECTION
74°
73°
72°
71°
70°
69°
68°
67°
41°
40°
39°
38°
37°
36°
LONG ISLAND
HUDSON CANYON
BLOCK CANYON
ATLANTIS CANYON
VEACH CANYON
HYDROGRAPHER CANYON
WELKER CANYON
OCEANOGRAPHER CANYON
GILBERT CANYON
LYDONIA CANYON
CARYN PEAK
top 1513 fms.
100
300
500
1000
1300
1500
1700
1900
2100
2300
2500
A156-15
A156-14
A156-10
A156-13
A161-2
A162-1
A156-8
A156-9
A161-1
A164-1
A156 11
A164-3
A164-2
A156-12
C10-13
C10 14
A164-4
A158-1
A164-6
A152-137
A164-7
A164-8
A164-5
A164-59
A164-60
A164-20
A164-10, 11
A164-22
A164-19
A158-2, 3, 4
A164-24
A152-135
A150-35
A164-23
A164-16
A164-15
A164-14
A167-2
A167-3
A164-17
A164-13

FIG. 2

or older fossils in the sands is not a serious objection, because they might have been non-fossiliferous to begin with, or the fossils might have been dissolved after deposition. What we do consider to be a final objection is that with hardly any exception the sands contain Pleistocene or Recent foraminifera characteristic of the continental shelf northwest of the Hudson Delta. Needless to say, the abyssal clays between the sands do not contain these shallow-water species. The theory of sedimentary vulcanism offers no explanation for the association of these foraminifera with the sands and only with the sands. On the other hand, the association points to a common source in relatively shallow water toward the northwest.

Positive evidence for transportation by turbidity currents is the distribution of the sands with respect to bottom topography. In the region of the Hudson Submarine Canyon sands and gravels have been found only in the canyon bed and not on the divides outside the canyon. This leads to the conclusion that the canyon has been the route of transportation, and that the agent has been some sort of flow under the influence of gravity, that is, turbidity currents.

If the sands of the plain southeast of the Hudson Canyon have been laid down by turbidity currents flowing through the submarine canyon, quantities of fine sediment of shallow-water origin ought to have been carried beyond the plain and into the North America Basin. Although we do not yet have a line of cores extending southeast from the sandy plain, we have evidence that very fine sediment of abnormally high calcium carbonate content has been deposited intermittently in various deep basins of the North Atlantic. Core A150-26 taken in the northeastern part of the Nares Basin from a depth of 5,670 m. (3,100 fm.) contains red clay of classic deep-sea facies to a depth of 55 cm., below which very sharply differentiated gray layers appear. Particle-size analyses show no consistent difference between the red and gray layers, but the average carbonate content of the gray layers is nearly twice that of the red layers, that is, 19 per cent against 9.7 per cent. Such fine gray relatively calcareous sediment, presumably of shallow-water origin, is exactly what a nearly exhausted turbidity current ought to deposit.

The possibility that the gray layers were deposited during times particularly favorable to lime secretion by planktonic organisms must be considered. In that case, within a region the gray layers should be continuous without regard to bottom relief. Instead, we find that two cores, A150-25 and A150-27, adjacent to A150-26 and from points 420 m. (230 fms.) shallower, are red clay throughout. Core A160-22 from a depth of 5,760 m. (3,150 fms.) or 90 m. deeper than A150-26, although a short core, contains gray layers, numerous silt films and one well sorted silt layer 4 cm. thick, while Core A160-1, less than 30 miles east of A160-22 and from a depth of 5,090 m. (2,780 fms.) or about 600 m. higher than either A160-22 or A150-26, contains neither gray layers nor silt layers, but is red clay throughout, with evidence of slow deposition in the form of abundant manganese oxide pellets, concretions, and many fish teeth. Reference to the list of cores makes clear that the few examples cited here are not the only ones showing that gray layers are found in cores taken in depressions but not in cores from submarine rises.

Evidently such differential deposition guided by depth should lead to relatively rapid filling of depressions, in turn giving rise to a characteristic bottom topography quite distinct from that to be expected from the deposition of a continuous blanket of sediment of uniform thickness on a bottom whose original relief was of tectonic origin. In the latter case the original degree of relief would remain unaltered. In the former, the expectable topography should consist of broad, very smooth, almost imperceptibly sloping plains from which there could rise abruptly here and there seamounts and ridges of tectonic or volcanic origin. A large number of fathograms now at the Lamont Geological Observatory show that the type of topography in the North Atlantic is that to be expected from the rapid filling of depressions by turbidity currents.[10]

In order to test the theory that deep basins and troughs receive much rapidly deposited sediment of shallow-water origin, early in 1951 a suite of cores was taken in and about the Puerto Rico Trough. The result was a complete confirmation. Two cores, A172-9 and A172-10, about 25 miles apart, were taken on the flat floor of the trough at 7,955 m. (4,350 fms.) depth. Both contain a top layer about 15 cm. thick of "red" or brown clay. The average calcium carbonate content of this layer is 0.5 per cent. Below this normal top there are in both cores three beautifully graded layers, one of which is about 200 cm. thick. The uppermost part of this graded layer is composed of clay-size particles, and is distinctly grayer than the normal top, but it is in its carbonate content of more than 36 per cent that it differs extraordinarily from a "typical" deep-water sediment. Downward in this layer there is a very gradual increase in particle size until near the base it becomes a well sorted calcareous sand largely composed of the tests of planktonic and benthic foraminifera, small pteropods, and alcyonarian spicules. The carbonate content near the base is 74 per cent. The very shallow-water origin of some of the material is shown by occasional particles of *Halimeda*. The shorter of these cores ends at 280 cm. still in well sorted material of shallow-water origin. The longer one at 295 cm. re-enters normal clay of abyssal facies and a carbonate content of 0.3 per cent, thereby effectively disposing of the theory that these layers of shallow-water material are evidence of a recent and sudden subsidence of the floor of the Puerto Rico Trough.

In 1873 the *Challenger* dredged at a point 70 miles east of the two cores just described. The description of the material obtained follows.[11]

> In this sounding—the deepest, 3,875 fath. (7,087 m.), taken by the *Challenger* in the Atlantic—the deposit was red on the surface, while the deeper layers were grayish and appeared to contain more $CaCO_3$ than the upper. The deposit brought home contains some pteropods and other molluscan shells and foraminifera, which appear to have come from a previous dredging, possibly from the same dredge having been used. During the early part of the cruise there was not so much care taken as later. There are, however, some things which indicate two distinct layers in this deposit.

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[10] Ivan Tolstoy and Maurice Ewing, "North Atlantic Hydrography and the Mid-Atlantic Ridge," *Bull. Geol. Soc. America*, Vol. 60 (1949), pp. 1537–40.

———, "Submarine Topography in the North Atlantic," *ibid.*, Vol. 62 (1951), pp. 441–50.

Bruce C. Heezen, Maurice Ewing, and D. B. Ericson, "Submarine Topography in the North Atlantic" (discussion of paper by Tolstoy), *ibid.*, Vol. 62 (1951), pp. 1407–09.

[11] John Murray, *Report of the Scientific Results of the Exploring Voyage of H.M.S. Challenger, 1873–1876* (1891). "Deep-Sea Deposits," p. 46.

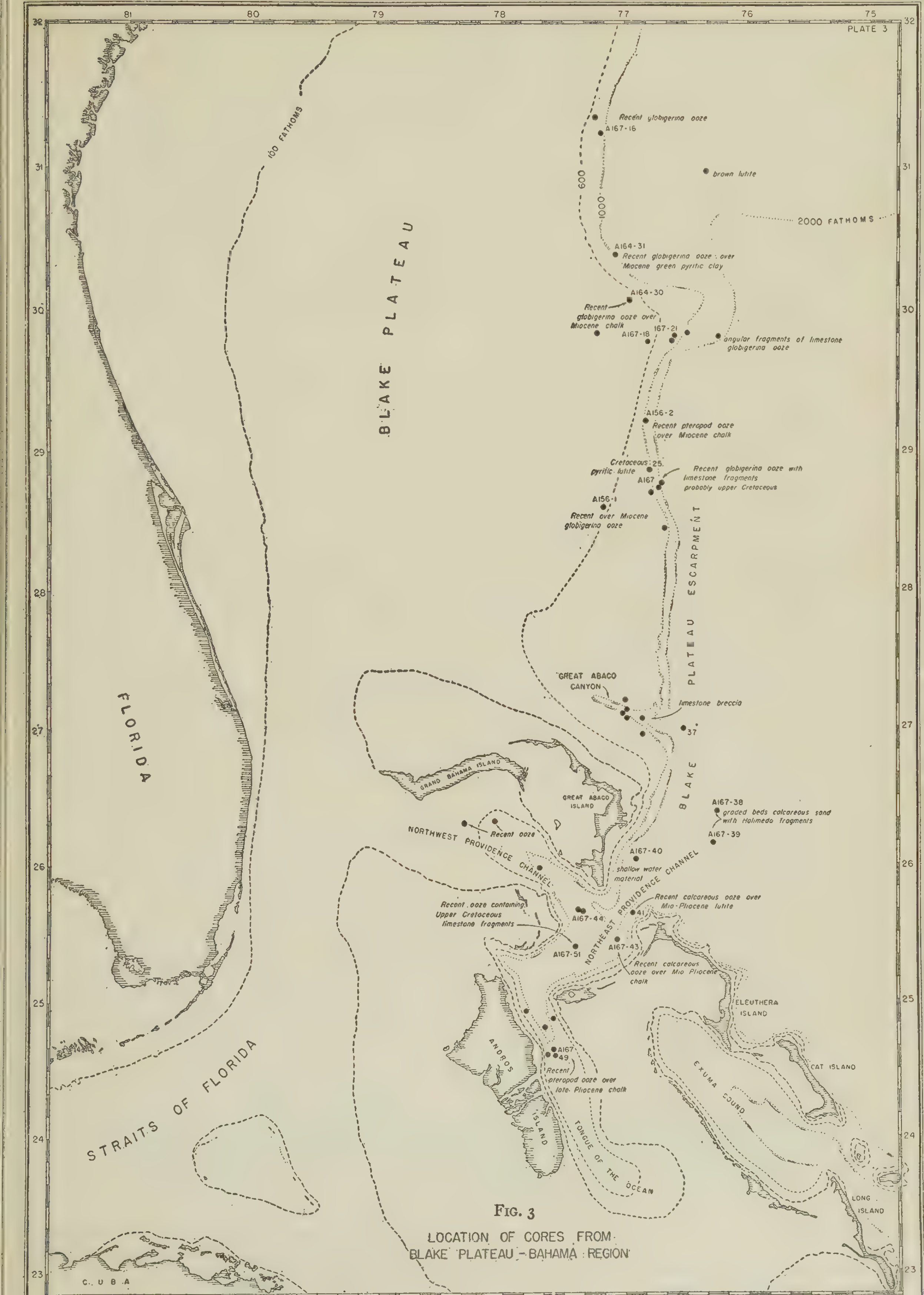
PLATE 3
81
80
79
78
77
76
75
32
31
30
29
28
27
26
25
24
23
100 FATHOMS
600
1000
2000 FATHOMS
BLAKE PLATEAU
FLORIDA
STRAITS OF FLORIDA
C U B A
Recent globigerina ooze
A167-16
brown lutite
A164-31
Recent globigerina ooze over Miocene green pyritic clay
A164-30
Recent globigerina ooze over Miocene chalk
A167-18
167-21
angular fragments of limestone globigerina ooze
A156-2
Recent pteropod ooze over Miocene chalk
Cretaceous pyritic lutite
25
A167
Recent globigerina ooze with limestone fragments probably upper Cretaceous
A156-1
Recent over Miocene globigerina ooze
BLAKE PLATEAU ESCARPMENT
GREAT ABACO CANYON
limestone breccia
37
GRAND BAHAMA ISLAND
GREAT ABACO ISLAND
A167-38
graded beds calcareous sand with Halimeda fragments
A167-39
Recent ooze
NORTHWEST PROVIDENCE CHANNEL
A167-40
shallow water material
NORTHEAST PROVIDENCE CHANNEL
Recent calcareous ooze over Mio-Pliocene lutite
41
Recent ooze containing Upper Cretaceous limestone fragments
A167-44
A167-51
A167-43
Recent calcareous ooze over Mio Pliocene chalk
ELEUTHERA ISLAND
A167
49
Recent pteropod ooze over late Pliocene chalk
ANDROS ISLAND
TONGUE OF THE OCEAN
EXUMA SOUND
CAT ISLAND
LONG ISLAND

FIG. 3

LOCATION OF CORES FROM BLAKE PLATEAU - BAHAMA REGION

We are inclined to think that they were more careful than they thought and that the dredge was quite clean when sent down.

Two cores, A172-11 and A172-15, taken on the northern side of the trough, contain only red clay although the thicknesses penetrated are 185 cm. and 290 cm. Another core, A172-16, from the top of the ridge north of the trough, is of "deep-water" facies throughout its length of 260 cm. in spite of the fact that the depth here is only 5,011 m. (2,740 fms.), that is, 2,900 m. (1,600 fms.) shallower than the bottom of the trough.

As the core profile is followed northward into the Nares Basin more red clay is found until a depth of 5,630 m. (3,080 fms.) is reached. Core A172-18 taken here consists of a series of red clay layers alternating with gray silty layers showing particle-size grading.

Other occurrences of coarse sediment of shallow-water origin at deep stations have been found southeast of the Bermuda Islands at the base of the Bermuda pedestal. An example is core A164-38 from a depth of 4,252 m. (2,325 fms.). It is composed entirely of graded shallow-water material. Not only are *Halimeda* particles abundantly present, but in the coarse lower part there are quantities of the shells and shell fragments of shallow-water clams some as much as 45 mm. in diameter. The objections to the theory that the shallow-water material was deposited at a time of greatly lowered sea-level are similar to those which apply to the Hudson Submarine Canyon region. For one thing, multiple uplift and subsidence become necessary to explain the fact that there are no less than seven alternations of graded shallow-water material with typical deep-sea ooze in the near-by core, A172-25, from a depth of 4,133 m. (2,260 fms.). Again, complete absence of normal globigerina ooze from the tops of both of these cores would lead to the absurd conclusion that subsidence of the Bermuda pedestal has taken place in historic time.

Further evidence against great lowering of sea-level is afforded by a group of cores taken east and southeast of the islands between the depths of 750 m. (410 fms.) and 3,000 m. (1,640 fms.). These contain sediments ranging in age from Pliocene to Eocene. Although the sediments from the shallowest of these stations are partly cemented, those from depths greater than 1,700 m. (930 fms.) show no trace of cementation or solution in spite of the fact that they contain abundant discoasters which are particularly sensitive to solution because of their small size, 10–15 microns in diameter, and their composition of aragonite. From this it is inferred that these sediments have not been subjected to percolating ground water, and, therefore, have not at any time since deposition been elevated above, or near sea-level.

In summary, it is the writers' opinion that the sedimentary relationships here outlined can best be explained by the theory of turbidity currents. We suppose that turbidity currents, generated in relatively shallow water through slumping, in sweeping across the 1,000–3,000-m. depth zone, have had sufficient erosive power to uncover sediments originally laid down in Eocene time. Where decrease

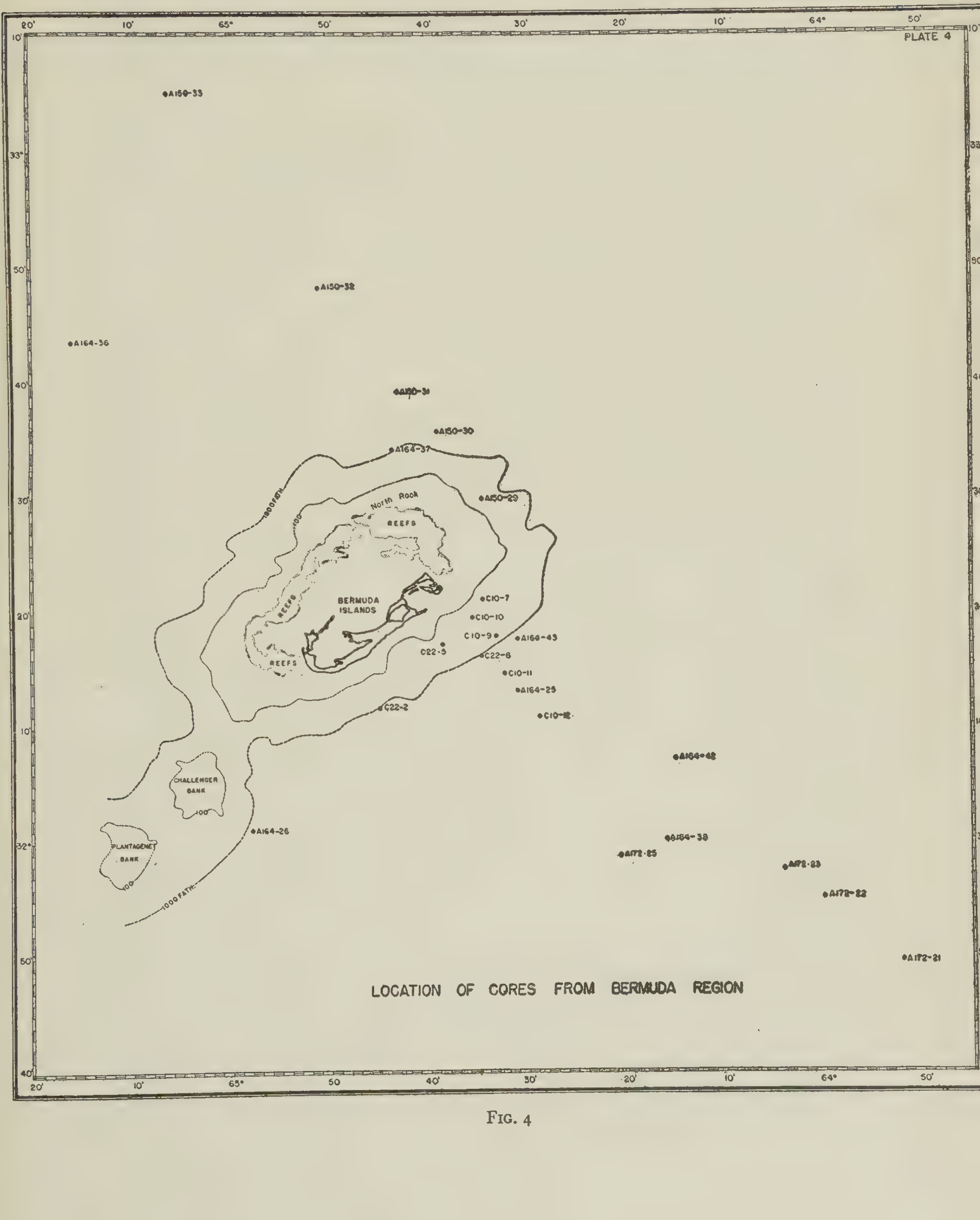
PLATE 4
20'
10'
65°
50'
40'
30'
20'
10'
64°
50'
33°
50'
40'
30'
20'
10'
32°
50'
40'
A150-33
A150-32
A164-36
A150-31
A150-30
A164-37
A150-29
North Rock
REEFS
1000 FATH.
100
BERMUDA ISLANDS
REEFS
REEFS
C10-7
C10-10
C10-9
A164-43
C22-5
C22-6
C10-11
A164-25
C22-2
C10-12
A164-42
CHALLENGER BANK
100
PLANTAGENET BANK
100
A164-26
1000 FATH.
A164-38
A172-25
A172-23
A172-22
A172-21

LOCATION OF CORES FROM BERMUDA REGION

FIG. 4

in the bottom slope occurs, deposition of the coarsest material, mostly of shallow-water origin, would be expectable. At the same time the finer sediment would be carried far out into the Nares Basin to be deposited as the gray abnormally calcareous layers which have already been noted.

A similar relationship between a shallow-water area of uncovered older sediments and abundant transported material of shallow-water origin in adjacent deep water occurs along the Blake Plateau. In several cores from the edge of the plateau the upper surface of the older sediment dips steeply and shows grooving in the direction of dip. Since in several places the older sediment is Eocene and in one Cretaceous it is very probable that the thickness of sediment removed has been large. It is safe to say that much of this material has found its way into the deep basins.

A seismic reflection survey by Hersey and Ewing[12] in the area bounded by Bermuda, the Greater Antilles, and the United States has shown that countless reflections are received from subsurface layers beneath basins having level floors. However, homogeneity of the subsurface sedimentary section beneath rises and topographic highs was shown by absence of subsurface reflections other than one or two from a considerable depth. This relationship, difficult to explain otherwise, is entirely expectable from the theory of turbidity-current deposition. An important conclusion to be derived from a study of the cores is that some of the criteria usually applied to sedimentary rocks for determining the depth of water and distance from shore in which the sediments were deposited are dangerously oversimplified.

Likewise most of the past work on dating deep-sea sediments and estimating rates of deposition has involved the assumption that reworking and horizontal transportation of sediment are negligible factors. The present work demonstrates that these factors are very important, so that the topographic and depositional environment of the sample must be known in oceanic work as well as in continental work. Whether the method of measurement is chemical, radiological, or paleontological, every possible clue from the lithologic character of the sample as well as from the topographic environment must be used to guard against introduction of serious errors through effects of sediments transported along the ocean floor. Certainly in the North Atlantic, most of samples taken from the floors of the main basins will have a large proportion of sediment deposited by turbidity currents. The Pacific Ocean, being bordered by effective sediment traps for this type of sediment along most of its circumference, and being also much larger, is probably affected by sediment of continental origin transported by turbidity currents to a much smaller extent. But from the impressive fan of calcareous detritus which has been accumulated at Bermuda and distributed widely by turbidity currents we may conclude that even in the Pacific Ocean one must not overlook the possibility that a specific sample may contain a serious amount of reworked material.

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[12] J. B. Hersey and Maurice Ewing, "Seismic Reflections from beneath the Ocean Floor," *Trans. Amer. Geophysical Union*, Vol. 30 (1949), pp. 5–14.

The large volume of quartz deep-sea sand discovered at the base of the continental rise is significant for geochemical calculations on silicon, such as the total volume of igneous rocks weathered, particularly since the suggested mechanism of deposition implies world-wide extent and is unlikely to be restricted to a single geologic period.

In a belt of the deep-sea floor about 2,000 miles long and 100 miles wide, sands form a predominant part of the sediment. Although there are some considerable gaps in coverage by cores, we consider that these cores have demonstrated that there is a continuous belt of sands located near the base of the continental rise in depths ranging from 4,600 meters (2,500 fms.) to 5,100 meters (2,800 fms.), extending from the southeast part of the Grand Banks to the Bahama Islands. The sediments are characterized by numerous layers of well sorted sands, commonly graded, consisting almost entirely of quartz in the north and of calcareous detritus in the south. The sands are interbedded with deep-sea clays. This deposit was produced by a process of transportation and sorting which has the same pattern from the Grand Banks to the Bahamas, regardless of the type of source material available. This fact is a powerful supplement to the arguments given elsewhere in this paper for the transportation of these sediments by turbidity currents.

1. Cores from Hudson Submarine Canyon Region

From echo-sounding traverses it is known that southeast of the Hudson Submarine Canyon there is a broad, gently sloping plain, the monotony of which is broken only by the Caryn Peak, a roughly cone-shaped feature which rises fully 1,800 m. (1,000 fms.) above the surrounding plain. Cores from the top of this mount show that it is of volcanic origin and that it has probably been in existence since the close of the Upper Cretaceous. Abrupt change in slope where the steep sides of the mount meet the surface of the plain strongly suggests that the plain has been, and probably still is, being built up around the mount by deposition of sediment coming from the Hudson Submarine Canyon and other canyons which converge on the plain.

Cores taken on the plain have been found to contain layers of well sorted sand and silt, which vary in thickness from films to beds more than 6 meters thick. Particle-size grading from coarse at the bottom to fine at the top is apparent in some layers, but not in all. The basal contacts of the sands are everywhere well defined. In a few, sand grades upward through silt into gray clay, but as a rule the upper contacts are marked by abrupt change from sand to clay. Apparently the slope of the plain is sufficient to prevent deposition of most of the silt and almost all of the clay-size particles in the turbidity currents which have transported and deposited the sands. Presumably the fine material was, and is, carried out into the basin toward the southeast.

Since the cores from the plain have already been discussed in the first part of this paper, it is sufficient here to list a few of the more significant cores from the canyon itself, cores in which there is evidence of the energy of the currents passing through the canyon and of the erosion which they have effected.

Core No.	*Depth**	*Lat. N.*	*Long. W.*	*Length*
A156-12	3,470 m. (1,900 fms.)	38°23′	70°57′	365 cm.

Location: In the bed of the canyon 90 miles southeast of the edge of the continental shelf.

To a depth of 75 cm. in this core foraminiferal clay layers alternate with fine micaceous sand. From 75 cm. to 100 cm. there is fairly clean gravel with the shells and shell fragments of various species of clams and snails. Below this and extending to the bottom of the core there is muddy gravel which becomes coarser downward. The pebbles of diameters to 2 cm. are largely composed of a variety of igneous, metamorphic, and hard sedimentary rocks. Horace G. Richards, who has examined the mollusks, has reported that they are Pleistocene in age, but that the possibility of faunal mixing is suggested by the presence of a few deep-water forms among many shallow-water species.

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* All depths from echo soundings using the standard velocity of 800 fms./second.

A164-7	3,820 m. (2,090 fms.)	37°57′	70°45′	212 cm.

Location: In the bed of the canyon, 120 miles from the edge of the shelf.

Clayey gravel with shell fragments and cobbles of a green pyritic clay which has been cored in the canyon walls.

A164-8	3,840 m. (2,100 fms.)	37°56′	70°44′	67 cm.

Location: Wall of the canyon a short distance below Core No. A164-7.

Green pyritic clay throughout. The clay contains *Nodogenerina georgiana* Cushman, *Globoquadrina* sp. and discoasters. The only trace of Recent sediment is as filling in burrows in the top of the core. The age is probably Miocene.

C10-13	3,570 m. (1,950 fms.)	38°22′	70°56′	419 cm.

Location: In the canyon about 90 miles from the edge of the shelf.

To 75 cm. layers of globigerina ooze alternate with green mud. The latter is probably reworked green pyritic clay. From 75 cm. to 142 cm.: layers of micaceous sand containing particles of green clay. From 142 cm. to 170 cm.: a confused zone of green clay fragments of pebble size in a sandy clay matrix. At 170 cm. the core enters homogeneous green pyritic clay which continues to the bottom of the core.

Five other cores from the walls of the canyon have brought up a similar green clay. All have been taken within that part of the canyon which extends 34 miles northeast of A164-8, a part which has been most closely cored. The fauna of the green clay varies somewhat from core to core, probably because a fairly large thickness of the clay is exposed in the canyon. Some of it is as old as Miocene, but certainly no older. The upper part is probably Pliocene in age. The fact that the canyon cuts this young clay is interesting evidence for the youth of the canyon.

A162-1	2,167 m. (1,185 fms.)	39°12′	71°48′	—

Location: Near the foot of the continental slope, 25 miles from the edge of the shelf.

No core was obtained but about 50 cubic centimeters of upper Eocene calcareous marl were recovered, together with several well rounded pebbles of quartzite and other hard rocks. Diameters of the pebbles reach 15 mm. The marl is fairly hard, but apparently this is due mainly to compaction, because it easily yields clean, uncorroded discoasters. Similar marl is known to crop out on the continental slope on both sides of the Hudson Canyon.*

A-164-5	3,028 m. (1,820 fms.)	37°46′	71°14½′	916 cm.

Location: 25 miles southwest of the Hudson Canyon and 110 miles southeast of the edge of the shelf

Except for two sand layers no more than a few millimeters thick at 670 cm. the core is entirely in clay. Species of foraminifera indicative of cold water extend from 50 cm. to the bottom. Evidently sediment of the Sangamon interglacial stage is not reached.

A164-6	3,676 m. (2,010 fms.)	38°08′	69°51½′	540 cm.

Location: 38 miles northeast of the Hudson Canyon and 120 miles south of the edge of the shelf.

This is entirely similar to A164-5, except that it contains no sand; hence, it is much more typical of inter-canyon sediments.

As the chart of the Hudson Canyon region shows, other cores have been taken in the area. They are not listed here because they are essentially similar to the foregoing examples.

2. CORES FROM CONTINENTAL RISE SOUTHWEST OF HUDSON CANYON

If turbidity currents have been responsible for the erosion of the Hudson Submarine Canyon and the building-up of the Hudson Delta, sediments similar to those of the delta ought to occur elsewhere along the continental rise. The following cores from stations scattered on or near the continental rise southwest of the Hudson Submarine Canyon show that in fact the Hudson Delta is not unique in the nature of its sediments.

Core No.	*Depth*	*Lat. N.*	*Long. W.*	*Length*
A164-34	5,030 m. (2,750 fms.)	34°57′	69°44′	234 m.

Location: On the continental rise near its base, 287 miles east of Cape Hatteras.

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* John Northtop and Bruce C. Heezen, "An Outcrop of Eocene Sediment on the Continental Slope," *Jour. Geol.*, Vol. 59, No. 4 (1951), pp. 396–99.

63% of the section cored is medium sand occurring as two beds one of which is 138 cm. thick. The interbedded sediment is brown clay of abyssal facies.

A167-4	4,846 m. (2,650 fms.)	34°56½′	70°05′	522 cm.

Location: The base of the continental rise, 267 mi. east of Cape Hatteras.

Layers of abyssal brown clay alternate with gray clay of shallow-water facies. Silt layers 1–2 mm. thick are common below 300 cm.

A167-5	5,118 m. (2,800 fms.)	34°09′	70°51′	964 cm.

Location: From the "flat" floor of the North America basin below the foot of the Continental Rise between Cape Hatteras and Bermuda.

A series of graded layers from a few centimeters to 30 cm. thick alternating with brown clay. In the graded layers silt or fine sand at the base passes upward into gray clay.

A167-6	5,010 m. (2,740 fms.)	33°59′	71°31½′	565 cm.

Location: 37 miles west-southwest of No. A167-5.

22% of the section is well sorted glauconitic sand in five layers, one of which is 58 cm. thick. In addition there are numerous silt layers of a few millimeters thickness. In the basal part of one sand layer there occur many sand grains of 2 mm. diameter and shell fragments to 6 mm. Brown and gray clay separate the sand layers.

A167-7	5,020 m. (2,750 fms.)	33°53½′	71°44′	520 cm.

Location: 12 miles southwest of No. A167-6.

Contains numerous gray clay layers with thin basal silt layers interbedded with brown clay. Distinct ripple marking on a small scale occurs in a silt layer at 483 cm.

A167-8	4,645 m. (2,540 fms.)	33°13′	73°39½′	630 cm.

Location: On the continental rise, near but not in a submarine canyon. 155 miles southeast of Cape Hatteras.

Numerous thin sand and silt layers alternate with brown and gray clay. When the energy of the falling coring tube is not sufficient to drive the full length of the tube into the sediment, it sometimes happens that sediment is forced to flow into the core barrel by the outside pressure when the piston is pulled up inside the core barrel. Structureless material of this kind is always easily distinguishable from the core proper with its original structure. Some sediment flowed into the coring tube at this station. In it there occurs a mass of coarse glauconitic sand containing abundant pyrite and shell fragments. In addition to the usual planktonic species of foraminifera there also occur in this sand the following shallow-water forms.

Amphistegina lessoni
Streblus beccarii
Marginulina bacheii
Elphidium incertum var. *clavatum*
E. cf. *gunteri*

Also in the sand are the following reworked fossil species.

Globotruncana arca
G. sp.
Gümbelina sp.
Inoceramus prisms

In this sand we have proof that the upper 6.3 meters of sediment are not really representative of what lies below, and that here, as at so many other stations, the evidence points to a drastic diminution in the frequency and power of turbidity currents in Recent time.

A167-9	4,645 m. (2,540 fms.)	33°14½′	73°41′	320 cm.

Location: On the continental rise, near but not in a submarine canyon, 2 miles northwest of A167-8.

Numerous silt layers from films to 5 or 6 mm. in thickness alternating with brown and gray clay.

A167-10	5,030 m. (2,750 fms.)	31°47′	73°24′	517 cm.

Location: On the continental rise near its base. 240 miles south-southeast of Cape Hatteras.

Numerous thin silt layers interbedded with red and gray clay. Between 280 cm. and 400 cm. frustules of the giant diatom, *Ethmodiscus gazelliae*, are abundant in thin layers. It is doubtful if occurrences of this kind, sporadic in areal distribution but fairly consistent vertically, can be accounted for by great proliferation of the species within a very restricted area of surface water. It seems more likely that these concentrations result from the purely mechanical effect of weak turbidity currents which sweep the tests together and deposit them in the same way that mica flakes appear to have been concentrated in some cores.

A167-11	4,870 m. (2,660 fms.)	31°48′	73°58½′	401 cm.

Location: On the continental rise near its base. 30 miles west of A167-10.

Contains seven graded beds with fine micaceous sand at the base grading up through silt into gray clay. In the lower part of the core there is one layer of fine sand 17 cm. thick. Only the top 25 cm. layer of the core is of really normal deep-water facies. Much evidence of burrowing by bottom-dwellers is confined to the upper parts of the graded layers. In no case is the sharply defined basal contact of a graded layer disturbed by burrowing. Apparently each graded layer records a fatal catastrophe to the bottom population, after which the population was renewed by recruits from adjacent areas sufficiently elevated to be safe from turbidity-current deposition.

3. Cores from Blake Plateau-Bahama Region

Core No.	*Depth*	*Lat. N.*	*Long. W.*	*Depth*
A156-1	1,005 m. (550 fms.)	28°35½′	77°10′	443 cm.

Location: 20 miles west of the edge of the Blake Plateau.

Below 350 cm. the foraminiferal assemblage is Miocene. Above 350 cm. Pleistocene species appear and gradually increase in number to 45 cm., above which the microfauna is Recent. Pteropods are common to abundant in the upper 50 cm. of the core but occur nowhere below. The absence of manganese oxide in this core opposes the view that there has been continuous but extremely slow deposition here since Miocene time. It appears more probable that the Miocene section was uncovered in late Pleistocene time and that the foraminifera of Miocene age occurring above 350 cm. have been eroded from near-by outcrops of Miocene ooze and redeposited here with the normal late Pleistocene and Recent species.

A156-2	2,140 m. (1,170 fms.)	29°12½′	76°49′	566 cm.

Location: Below the edge of the Blake Plateau on the steep escarpment.

15 cm. of Recent pteropod ooze on fine-grained Eocene chalk. The contact is sharply defined but is without manganese oxide.

A164-30	1,080 m. (590 fms.)	30°04′	76°57′	819 cm.

Location: On the Blake Plateau just west of the edge.

150 cm. of Recent and Pleistocene globigerina ooze overlying Miocene chalk. The contact is well defined, but without manganese oxide. However, the Miocene chalk is stained to a rusty color several centimeters below the contact, and contains vertical burrows filled with iron and manganese oxide to 15 cm. below the contact.

A164-31	1,865 m. (1,020 fms.)	30°23′	77°04′	380 cm.

Location: Below the edge of the Blake Plateau on the steep slope.

54 cm. of Recent globigerina-pteropod ooze overlying Miocene green pyritic clay. The well defined contact dips 15°. To a depth of about one meter below the contact pyrite has been oxidized and some manganese oxide has been introduced.

A167-21	1,455 m. (795 fms.)	29°49′	76°35′	365 cm.

Location: Just below the edge of the Blake Plateau on the escarpment.

Upper Eocene chalk throughout. There is a thin manganese oxide crust at the top to which a few Recent foraminifera adhere.

A167-25	1,750 m. (955 fms.)	28°52′	76°47′	110 cm.

Location: Below the edge of the plateau on the escarpment.

Dark green somewhat sandy pyritic lutite. Except for a little globigerina ooze filling a burrow near the top of the core, no Recent sediment is present. The pyrite is oxidized to a depth of 16 cm. from the top. A rather meager microfauna indicates that the age is Cretaceous, and probably Lower Cretaceous.

A167-37	4,760 m. (2,600 fms.)	26°59′	76°31′	447 cm.

Location: From Great Abaco Canyon below the base of the Blake Plateau escarpment.

The upper part is tan calcareous lutite which grades downward into calcareous sand at 70 cm. The sand rests on a dark gray clay containing a Pleistocene or late Pliocene microfauna indicative of cooler water than that of the present time. The gray clay is compacted but not indurated. It contains only 14% calcium carbonate in contrast to the 56% calcium carbonate of the Recent tan lutite. Except for the occurrence of pyrite below 210 cm. the gray clay is uniform from top to bottom.

The contact between the calcareous sand and the gray clay is extraordinary in that it dips at an angle of about 80° as measured from a plane perpendicular to the axis of the core. Bedding planes in the calcareous sand directly above the contact show that the core barrel must have been essentially vertical when the contact was cored. Further, the undisturbed bedding of the overlying sand shows that the angle of the contact plane can not have resulted from distortion of an originally horizontal contact through friction against the coring-tube wall during coring or extrusion. Faulting is precluded by complete absence of disturbance of the bedding planes of the sand where they end against the clay.

The most satisfactory explanation is that the sand was deposited against the steep side of a gully by a turbidity current. Admittedly, so steep a slope in unconsolidated clay could not be expected to remain standing long without slumping. That it did not slump may be an indication that the excavation of the gully itself was due to erosion by the same turbidity current which transported and deposited the sand. Since the height of the slope as measured in the core is only 24 cm. there is no reason to assume that the gully was at all deep, and the current which had sufficient energy to transport the sand could certainly have eroded the clay to a depth of half a meter or more, particularly during the first vigorous onset. Later, when the velocity had somewhat decreased, the sand was deposited in the channel which had been excavated perhaps only a few hours previously. Some decrease in current velocity is evident in the graded bedding of the sand.

A167-38 4,630 m. (2,530 fms.) 26°23′ 76°14′ 262 cm.

Location: From the "flat" ocean floor east of Great Abaco Island.

Contains several graded layers of calcareous sand, one of which is 90 cm. thick. Particles of *Halimeda* are abundant in a well sorted calcareous sand at 210 cm.

A167-39 4,627 m. (2,530 fms.) 26°09′ 76°16′ 914 cm.

Location: From the "flat" ocean floor northeast of the Northeast Providence Channel.

This, also, includes several graded layers of calcareous sand with abundant particles of *Halimeda.* The lower part of one such layer, 180 cm. thick, could easily be mistaken for a calcareous beach sand. The foraminifera indicate that the time of deposition was late Pleistocene. This is the most southerly core reported in this paper in which the sorted and graded sand layers satisfy perfectly our criteria for turbidity-current transportation and deposition along the western edge of the deep-sea basin.

A167-41 3,109 m. (1,700 fms.) 25°39′ 76°56′ 488 cm.

Location: On the south wall of the Northeast Providence Channel.

Foraminiferal lutite extends to 215 cm., at which depth there is a well defined contact dipping at 45°. Below the contact greenish gray clay containing discoasters and Mio-Pliocene foraminifera extends to the bottom of the core. Pyrite in the Neogene clay has been oxidized to a depth of about 25 cm. The sequence of foraminifera in the section above the contact shows that when deposition recommenced the climate was cooler than it is now.

A167-43 2,580 m. (1,410 fms.) 25°27′ 77°03½′ 510 cm.

Location: On the south wall of the Northeast Providence Channel, near Eleuthera Island.

It consists of Pleistocene to Recent globigerina ooze to 150 cm., resting on chalk containing a Neogene fauna and discoasters. A depositional hiatus in the Pleistocene section at 60 cm. is indicated by manganese oxide deposition and an abrupt change from a fauna characteristic of relatively cool water to the fauna which is now living in the region.

A167-44 2,490 m. (1,360 fms.) 25°39½′ 77°21′ 475 cm.

Location: On the northeast wall of the Northwest Providence Channel canyon.

Recent and Pleistocene globigerina ooze extends to 110 cm. where there is a well defined contact with compacted but not cemented Miocene chalk below. Pyrite in the chalk has been oxidized to 120 cm. below the contact. The sequence of foraminifera in the Pleistocene section shows that a colder climate prevailed when deposition recommenced.

A167-49 1,740 m. (950 fms.) 24°36′ 77°34′ 370 cm.

Location: Near the center of the Tongue of the Ocean.

113 cm. of Pleistocene globigerina ooze overlying chalk which is probably late Pliocene in age. The contact surface dips 18° and shows faint grooving parallel with the direction of dip. The top of the core contains *Globorotalia tumida* var. *flexuosa* Koch. In the normal Pleistocene sequence in the North Atlantic this variety occurs below a cool-water zone and from one to several meters below the surface. It is, therefore, inferred that some part of the Pleistocene-Recent section has been removed by slumping or submarine erosion.

A167-51 3,383 m. (1,850 fms.) 25°23½′ 77°24′ 255 cm.

Location: From the floor of the submarine canyon north of New Providence Island.

This core, of Pleistocene-Recent deposition throughout, is of interest because particles and cobbles of fairly hard chalk containing *Globotruncana arca* and *Gümbelina* sp. occur in the lower part, indicating that Upper Cretaceous sediments must crop out at no great distance from this station.

The last five cores described in this section show that removal of material from intermediate depths during the late Pleistocene, at least, has been a process of importance in the modification of bottom topography. They also help to explain the source of the large quantities of sediment of shallow-water origin now being found at great depths. It is possible that in some places the older sediments have been uncovered by slumping, but probably the most frequent cause has been erosion by turbidity currents generated in shallow water. The fact that so commonly the older sediment is covered by no more than a thin layer of very late Wisconsin ooze supports the theory that here, as elsewhere, low sea-level of the glacial stages had much to do with the frequency and energy of turbidity currents.

Proof that erosion has cut through the Upper Cretaceous affords a measure of its importance and suggests that this form of submarine erosion may be largely responsible for excavation of the Tongue of the Ocean and the Providence channels.

As the accompanying chart of the Blake Plateau-Bahama region shows, other cores have been taken in this area. These are not described here because, however interesting they may be as records of Pleistocene climatic change, they do not contain direct evidence bearing on the problem of turbidity currents.

4. Cores from Bermuda Pedestal and Surrounding Bermuda Rise

Core No.	*Depth*	*Lat. N.*	*Long. W.*	*Length*
A150-30	1,795 m. (980 fms.)	32°35½′	64°39′	24 cm.

Location: 9.3 miles northeast of North Rock.

The top is a fine calcareous sand which grades downward into calcareous gravel containing limestone fragments to one centimeter in diameter.

A150-31	2,798 m. (1,530 fms.)	32°39′	64°43′	92 cm.

Location: 10.8 miles north of North Rock.

Fairly uniform globigerina ooze except for a layer 5 cm. thick of well sorted calcareous sand 15 cm. from the top containing many fragments of *Halimeda*.

A150-33	4,580 m. (2,500 fms.)	33°05′	65°06′	303 cm.

Location: 43 miles northwest of North Rock.

Globigerina ooze alternating with layers of loose calcareous sand 3–20 cm. thick, containing species of foraminifera characteristic of shallow water, as well as reworked forms from some of the older sediments which crop out on the sea bottom around Bermuda.

A164-25	2,871 m. (1,570 fms.)	32°13′	64°31′	360 cm.

Location: 9.7 miles southeast of Castle Harbor.

To 45 cm. it is a mixture of Recent ooze with reworked older foraminifera and fragments several centimeters in diameter of white chalk. From 45 cm. to the bottom the core is white homogeneous chalk containing foraminifera which show that it is certainly not younger than Miocene. *Almaena alavensis* (D. K. Palmer), found in the Oligo-Miocene of Cuba, occurs in the lower part of the chalk.

A164-26	2,706 m. (1,480 fms.)	32°01′	64°58′	63 cm.

Location: East flank of the Challenger Bank.

To 41 cm., calcareous sand containing Pleistocene foraminifera and abundant fragments of hard limestone embedded in which there are fragments several centimeters in diameter of a coarse-grained alkaline pyroxenite (examined by H. H. Hess and J. T. Fyles). Beneath this there is white chalk containing a Miocene microfauna.

A164-36	4,517 m. (2,470 fms.)	32°43½′	65°16′	467 cm.

Location: 30 miles northwest of North Rock.

This contains four layers of well sorted calcareous sediment having a total thickness of 316 cm. These show good particle-size grading from coarse material at the base to calcareous silt at the top. Except for a few reworked species the foraminifera are throughout of Pleistocene age. Significant is much material of shallow-water origin in the coarser parts. This includes an abundance of *Amphistegina lessoni*, *Homotrema rubrum*, and particles of *Halimeda* 5 mm. in diameter.

A164-38	4,250 m. (2,325 fms.)	32°00′	64°16′	173 cm.

Location: 30 miles southeast of the Bermuda Islands.

From the top, composed of coarse calcareous silt, there is complete gradation downward into calcareous gravel at the bottom of the core. The well sorted material of sand size between 50 cm. and 100 cm., which contains much *Halimeda* débris, is remarkably similar to the calcareous sand of the Bermuda beaches.

The sample caught in the cutting edge of the coring tube below 173 cm. contains clam shells and shell fragments as much as 45 mm. in diameter together with pebbles of limestone and igneous rock of diameters reaching 18 mm.

Very recent deposition of the sediment in this core is shown by the complete absence of normal poorly sorted deep-sea sediment above the calcareous silt. The median diameter of the silt is 62μ, while its mean quartile deviation has the remarkable value of 0.45ϕ. Removal of normal deep-sea sediment by bottom scour can not be admitted because any current with sufficient energy to remove the large tests of planktonic foraminifera would necessarily also remove the loose silt at the top of the core.

A164-42 4,240 m. (2,320 fms.) 32°07′ 64°15′ 575 cm.

Location: Southeast of Bermuda, and 7 miles north of A164-38.

This contains several graded layers of sand composed largely of shells and calcareous débris of shallow-water origin interbedded with normal globigerina ooze. Unlike A164-38, the uppermost layer is a globigerina ooze normal for the depth and position.

A164-43 2,085 m. (1,140 fms.) 32°17½′ 64°31′ 28 cm.

Location: 8 miles southeast of St. David's Head.

The top is a 20-cm. graded layer containing shallow-water species of foraminifera and *Halimeda* particles, which overlies unsorted globigerina ooze of normal deep-water facies. In the bottom of the core are several pebbles of sandstone composed of rounded granules of igneous rock and minerals in a calcareous matrix.

A172-21 4,499 m. (2,460 fms.) 31°49½′ 63°52′ 270 cm.

Location: 55 miles southeast of the Bermuda Islands.

Contains five graded layers 20–35 cm. thick of well sorted calcareous sand with abundant *Halimeda* particles, interbedded with brown and red clay of normal facies for the depth.

A172-22 4,480 m. (2,450 fms.) 31°55′ 64°00′ 80 cm.

Location: 43½ miles southeast of Bermuda, on a 4,480-meter (2,450 fms.) terrace.

This shows excellent particle-size gradation from very fine well sorted calcareous sand at the top to medium calcareous sand at the bottom. At least half of the material composing the sand is of very shallow-water origin.

A172-23 4,352 m. (2,380 fms.) 31°57½′ 64°04′ 355 cm.

Location: 35 miles southeast of the Bermuda Islands.

Contains well sorted graded layers as much as 90 cm. thick interbedded with normal deep-sea clay.

A172-25 4,133 m. (2,260 fms.) 31°58½′ 64°20½′ 560 cm.

Location: 27 miles southeast of the Bermuda Islands.

The top is a graded layer of calcareous sand 26 cm. thick. The rest of the core is a series of graded layers interbedded with calcareous clay of normal facies.

Complementary to these cores, which show evidence of rapid deposition in deep water by turbidity currents, is another series from shallower water, that is, between 1,000 and 3,000 meters, which give evidence of submarine erosion. Apparently the energy of the turbidity currents which have swept across this zone of steeper slope has been, and locally still is, sufficient to prevent deposition, or even to erode the uncemented pre-Pleistocene sediments which occur here. Among such cores are the following.

C10-7 1,150 m. (630 fms.) 32°20.9′ 64°34.5′ 287 cm.

Location: 4 miles east of St. David's Head.

25 cm. of Recent globigerina ooze overlies coarsely granular chalk containing foraminifera which are possibly early Pleistocene or more probably Pliocene. The contact at 25 cm. is well defined, but not marked by manganese oxide.

C10-10 1,060 m. (580 fms.) 32°19.4′ 64°35.6′ 182 cm.

Location: 3½ miles southeast of St. David's Head.

This is Miocene chalk throughout. The top is slightly impregnated with manganese oxide. Nowhere is there any trace of particle-size sorting or grading, or any admixture of Recent species. Absence of discoasters and incipient cementation suggest that there has been at least limited circulation of water through this sediment at some time in its history.

C10-11 2,230 m. (1,220 fms.) 32°14.5′ 64°32.3′ 198 cm.

Location: 9 miles southeast of St. David's Head.

The core is entirely coccolith-discoaster ooze. The foraminifera indicate that the age is late Eocene or Oligocene. There is no manganese oxide at the top or any trace of Recent sediment.

C22-2 1,939 m. (1,060 fms.) 32°11½′ 64°45′ 140 cm.

Location: 4½ miles southeast of Gibbs Hill, Hamilton Island.

A 33 cm. layer of Recent globigerina ooze overlies altered volcanic ash. The contact dips at about 20°. Foraminifera in the ash are rare and not diagnostic, but abundant coccoliths and discoasters show that the ash was probably deposited in late Eocene or Oligocene time.

The two following cores also contain altered volcanic ash underlying only a thin layer of Recent sediment.

C22-5	1,100 m. (600 fms.)	32°17′	64°38½′	120 cm.

Location: 4¾ miles south of St. David's Head.

C22-6	1,509 m. (825 fms.)	32°16′	64°34¾′	188 cm.

Location: 8 miles southeast of St. David's Head.

5. CORES FROM CARIBBEAN

In this suite of seven cores from the Caribbean we find further evidence that deposition on submarine elevations is slow and uniform, while on slopes and particularly in depressions the monotony of deposition may be broken by slumping and mud flow or by rapid, really instantaneous deposition of coarse material of shallow-water origin transported by turbidity currents.

Core No.	*Depth*	*Lat. N.*	*Long. W.*	*Length*
A172-1	4,169 m. (2,280 fms.)	17°14′	73°28′	488 cm.

Location: On the side of a small hill rising 180 m. (100 fathoms) above the 4,150 m. (2,270-fm.) floor of the northeast extension of the Colombian basin.

From top to bottom this is a dark brown clay with abundant foraminifera. Nowhere is there a sorting of particle sizes or material of shallow-water origin.

A172-2	3,077 m. (1,680 fms.)	16°12′	72°19′	493 cm.

Location: On a terrace-like feature, 10 miles east of the Crest of the Beata Ridge.

A uniform globigerina ooze throughout except for two layers, 1 and 3 cm. thick, at 370 cm. and 430 cm., composed of well sorted shells of foraminifera. No material of shallow-water origin is present. In the two thin well sorted layers is evidence of very rare and weak turbidity currents, whose place of origin was presumably on the slope of the Beata Ridge.

A172-3	3,338 m. (1,825 fms.)	15°56′	72°02′	563 cm.

Location: On a gently sloping bottom on the southeast flank of the Beata Ridge.

To 390 cm. the core is in uniform globigerina ooze. In the lower part gray, tan and brown clays are mingled in such a way as to give a marbled effect, evidently as a result of slumping and flow over a short distance in a fairly viscous state. No material of shallow-water origin is present.

A172-4	3,841 m. (2,100 fms.)	14°39′	70°49′	845 cm.

Location: On the east flank of the Beata Ridge.

It is in structureless globigerina ooze to 500 cm., below which occur several layers, 4 or 5 cm. thick, of well sorted shells of foraminifera. Again there is no material of shallow-water origin.

In this core, as in many others, there is evidence that turbidity currents are less frequent and effective now than they were formerly. In parts of the North Atlantic this is probably due to submergence of the continental shelves following recession of the Wisconsin ice sheets. However, turbidity currents reaching this station can hardly have come from elsewhere than the Beata Ridge, which is covered by fully 2,000 meters of water. It is difficult to understand how change of sea-level by 200 meters could make any difference in this case. It is suggested that decrease in frequency of turbidity currents might be an indication of a decrease in seismic activity in late Pleistocene time.

A172-5	3,146 m. (1,720 fms.)	13°20′	69°51′	730 cm.

Location: On a local elevation on the continental slope north of Aruba.

This is very uniform calcareous lutite with abundant foraminifera throughout.

A172-6	4,160 m. (2,275 fms.)	14°59′	68°51′	935 cm.

Location: On the crest of an eastern extension of the Beata Ridge.

A very uniform core in which only the proportion of foraminifera varies, presumably as a consequence of climatic change.

A172-7	4,883 m. (2,670 fms.)	16°55′	67°30′	1,067 cm.

Location: On a gently northward sloping bottom several miles from the deepest part of the Dominican Trough on this profile.

This, the deepest core on the traverse, contains no less than eight graded layers. A calcareous sand, containing such material of shallow-water origin as *Archaias* sp., *Amphistegina lessoni*, alcyonaria spicules, and particles of *Halimeda*, makes up the lower part of the thickest of these layers. This 76-cm. layer occurs at 900 cm. The great contrast in character of sediment between this and the other Caribbean cores is easily understandable on the hypothesis that the sands in it were deposited by turbidity currents since this is the only one of the Caribbean cores which is from the bottom of a basin. To date this is the southernmost core in the writers' collection in which evidence of turbidity-current transportation has been found.

These conclusions raise the question of whether the evidence of climatic fluctuations deduced by Phleger* from a study of the foraminifera in *Albatross* Core 30 taken in the eastern part of the Venezuelan Basin may be instead evidence of successive turbidity currents which deposited material eroded from higher on the Aves Ridge. A study of the lithologic character and associated fauna in this core should reveal the correct explanation.

6. Cores from Puerto Rico Trough

Core No.	*Depth*	*Lat. N.*	*Long. W.*	*Length*
A172-9	7,955 m. (4,350 fms.)	19°48½′	66°11′	280 cm.

Location: On the flat floor of the Puerto Rico Trough.

"Red" or brown clay containing 0.2% of carbonate extends to 19 cm. Beneath this the section consists of three graded layers, the thickest of which measures more than 200 cm. At the base of each layer there is calcareous sand largely composed of the tests of small benthic species of foraminifera together with a generous number of alcyonarian spicules. Quartz particles are present to the extent of no more than 5%. The sands grade upward into a sediment of clay consistency with over 36% calcium carbonate.

A172-10	7,955 m. (4,350 fms.)	19°45′	66°37′	397 cm.

Location: On the floor of the Puerto Rico Trough, 25 miles west of No. A172-9.

This core is very similar to A172-9. The upper layer of brown clay has a calcium carbonate content of 0.8%. At 50 cm. in the upper clayey part of a graded layer the carbonate content is 37%, and this increases downward to 74% at 218 cm. where there is well sorted calcareous sand. Below 272 cm. the core again enters normal deep-sea clay with 0.3% carbonate. Fragments of *Halimeda* and *Homotrema rubrum* occur in the coarse lower part of the thickest graded layers.

A172-12	6,630 m. (3,625 fms.)	19°28′	65°04′	178 cm.

Location: Near the base of the south wall of the trough.

Normal brown clay to 16 cm. From 16 cm. to 63 cm. there is some indication of slumping or mud flow. From 63 to 80 cm. the core is finely laminated with numerous silty layers about 2 mm. thick. The lower part of the core is brown clay except for a single gray silty layer 5 cm. thick.

A172-13	6,398 m. (3,500 fms.)	19°24′	65°07′	98 cm.

Location: Steep south wall of the trough.

Evidence of slumping and flow throughout. Foraminifera are rare except for a few lenses of well sorted tests. The entire section is Pleistocene. *Amphistegina lessoni* and *Halimeda* fragments occur in the bottom sample.

A172-14	7,132 m. (3,900 fms.)	19°54′	64°48′	300 cm.

Location: Floor of the Puerto Rico Trough 85 miles east of the other deep sea cores.

Alternating layers a few centimeters thick of red and light tan clay. At 200 cm. there is a one millimeter layer of clean quartz silt.

A172-15	5,887 m. (3,220 fms.)	20°13′	64°56′	290 cm.

Location: North wall of Puerto Rico Trough.

Typical deep-sea red clay throughout.

A172-16	5,011 m. (2,740 fms.)	20°42′	64°43′	260 cm.

Location: Top of the ridge north of the Puerto Rico Trough.

Entirely red clay.

7. Cores from North America Basin

Good evidence of the relationship between bottom topography and bottom sediment is afforded by a series of cores extending from the Puerto Rico Trough northward toward Bermuda. From

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* Fred B. Phleger, "Foraminifera of a Submarine Core from the Caribbean Sea," *Medd. Ocean. Inst. Göteborg*, 2, No. 16 (1948).

Station A172-16 at 5,195 m. (2,840 fms.) the bottom slopes very gradually down to the north until at A172-17 the depth has increased by about 400 meters.

Core No.	*Depth*	*Lat. N.*	*Long. W.*	*Length*
A172-17	5,612 m. (3,070 fms.)	22°46′	63°58½′	378 cm.

Location: Southwest part of the Nares Basin, 130 miles north of the top of the ridge north of the Puerto Rico Trough.

In striking contrast to Core A172-16, which gave evidence of very slow and uniform deposition, this core contains at least 18 graded layers alternating with brown clay of abyssal facies. At least ¾ of the thickness of sediment penetrated here has been deposited by turbidity currents. The basal contacts of the graded layers are sharply defined by abrupt change from brown clay to gray silty micaceous clay, or even to clean quartz silt. The "abnormality" of the graded layers is further shown by the absence of material coarser than 74 microns diameter. In slowly deposited deep-sea brown clays small teeth, sporadic quartz grains a millimeter or more in diameter, and rare benthic foraminifera are expectable. The absence of such material in the graded layers is in good keeping with the mode of origin, that is, relatively rapid deposition of particles transported in suspension by a slowly moving turbidity current.

A172-18	5,630 m. (3,080 fms.)	23°40′	64°04′	100 cm.

Location: Southwest of the central part of the Nares Basin, 55 miles north of A172-17.

At least four graded layers alternate with red clay. No really clean silt is present but there is marked increase in the proportion of silt in the lower parts of the graded layers. Again, fully three quarters of the thickness penetrated has been deposited as graded layers. A sample taken at 50 cm. in gray clay when washed on a 74-micron sieve yielded a surprisingly large quantity of finely divided mica and vegetal débris, material which might easily be wafted along by a very gentle current.

A172-19	5,209 m. (2,850 fms.)	24°35′	64°02′	505 cm.

Location: Southwest part of the Nares Basin on a small hill near the south boundary of the Bermuda Rise.

This is uniform brown clay throughout.

A160-11	5,725 m. (3,130 fms.)	25°34′	62°11′	120 cm.

Location: Central part of the Nares Basin. 150 miles northeast of A172-19.

At this deep station a series of alternating layers of dark brown, tan, and gray clay have been deposited. In the lower part of the core there are numerous thin silt layers.

On the other hand, the following cores north of A160-11 contain red clay alone.

A160-12	5,400 m. (2,955 fms.)	27°17′	62°07′	270 cm.

Location: North-central part of the Nares Basin.

A160-13	5,667 m. (3,100 fms.)	27°45′	61°54′	71 cm.

Location: North-central Nares Basin.

A160-14	5,110 m. (2,795 fms.)	28°41′	61°55′	387 cm.

Location: North of Nares Basin on the Bermuda Rise.

A164-40	5,316 m. (2,910 fms.)	28°38½′	61°37′	312 cm.

Location: North of the Nares Basin.

A164-41	5,577 m. (3,050 fms.)	28°24½′	60°09′	85 cm.

Location: North part of the Nares Basin.

Stations at which further evidence of turbidity currents has been found are the following.

A153-164	5,670 m. (3,100 fms.)	21°46′	60°18′	124 cm.

Location: Southern part of the Nares Basin.

An 84 cm. layer of brown clay with 2.3% calcium carbonate overlies gray clay with 10% calcium carbonate. Burrowing animals have been active in the brown clay. The gray layer is without any evidence of them.

A160-22	5,760 m. (3,150 fms.)	30°10′	58°22′	121 cm.

Location: Northern part of the Nares Basin.

Layers of gray clay alternate with red. A few thin silt layers occur in the lower part of the core.

A160-16	5,390 m. (2,945 fms.)	31°19′	55°48′	486 cm.

Location: On the 5,200–5,400-m. (2,850–2,950-fm.) plain between the Mid-Atlantic Ridge and the Bermuda Rise.

Alternating layers of red clay and gray clay with numerous thin layers of quartz silt.

A153-141	5,350 m. (2,925 fms.)	33°26½′	53°48′	1025 cm.

Location: The flat floor of the ocean basin on the 5,200–5,400-m. (2,850–2,950 fm.) plain.

Red clay of normal deep-sea facies extends to 30 cm. below which is a series of alternating layers of red clay, gray clay, and quartz silt to 400 cm. From 400 to 600 cm. there is micaceous glauconitic sand. At 460 cm. the sand has a median diameter of 110 microns and is well sorted, having a quartile deviation of 0.7ϕ. Between 600 and 718 cm. there is a series of brown clay layers alternating with silt and sand. From 718 cm. to the bottom of the core there is again glauconitic sand, which has at 790 cm. a median diameter of 103 microns and is also well sorted, having quartile deviation of 0.8ϕ. The lower sand layer shows a gradual increase in particle size downward. Both sand layers contain a few foraminifera among which are the shallow-water benthic forms *Elphidium incertum* var. *clavatum*, *Elphidiella arctica*, and *Nonion labradoricum*.

A152-130	5,400 m. (2,955 fms.)	34°34′	51°04′	485 cm.

Location: The flat floor of the North America Basin on the 5,200-5,400-m. (2,850-2,950 fm.) plain between the Mid-Atlantic Ridge and the Bermuda Rise.

85 cm. of brown clay with 11% calcium carbonate overlie 4 meters of gray clay with 23% calcium carbonate. The core is without sand or silt and the lower gray part is almost devoid of foraminifera.

A152-127	4,630 m. (2,530 fms.)	34°56′	46°19′	786 cm.

Location: West flank of the Mid-Atlantic Ridge.

Brown clay alternates with gray clay, with the latter making up about ¾ of the section. Sand and silt are absent.

A157-16	5,230 m. (2,860 fms.)	36°47′	48°01′	317 cm.

Location: On the 5,200-5,400-m. (2,850-2,950 fm.) plain south of the Grand Banks.

An alternation of brown and gray clay layers throughout.

A157-11	4,775 m. (2,610 fms.)	41°34′	43°24′	858 cm.

Location: Floor of the Newfoundland Basin southeast of the Grand Banks.

Brown clay alternating with gray silty layers. Numerous silt layers appear in the lower part of the core. *Elphidiella arctica* occurs in the gray layers.

A157-12	4,870 m. (2,660 fms.)	42°00′	45°22′	301 cm.

Location: The floor of the Newfoundland Basin south of the Flemish Cap and north of the Gulf Stream.

Layers of gray clay alternate with silt and well sorted fine sand. One graded layer has a thickness of 35 cm. This is the most northerly core reported in this paper and the sorted and graded sand layers in it satisfy perfectly our criteria for turbidity current deposition near the foot of the continental rise.

The following three cores, all of which were taken south of Sable Island on the continental rise near its base, are similar in containing gray clay with silt or graded sand layers interbedded with brown clay of abyssal facies.

A164-46	4,760 m. (2,600 fms.)	41°24′	59°02′	281 cm.
A164-47	4,720 m. (2,580 fms.)	41°43′	59°00′	71 cm.
A164-48	4,630 m. (2,530 fms.)	41°35′	59°53′	483 cm.

Contribution No. 606

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ADDITIONAL NOTES ON THE DISTRIBUTION OF THE BLACKFIN TUNA (*PARATHUNNUS ATLANTICUS*).—Until recently the recorded northern limits of occurrence of blackfin tuna, *Parathunnus atlanticus* (Lesson), had been off the coast of Bermuda, and off Florida along the United States coast (Beebe and Tee-Van, 1936, Zoologica, 21 (3): 177–94). In 1951 we reported one specimen taken off the coast of North Carolina (1951, COPEIA, (3): 248), and thus extended considerably its reported northern range along the United States coast. Since that report, we have obtained additional information on the distribution of the species.

In October 1948, a tuna (29 cm. in length) was caught about 75 miles south of Martha's Vineyard (40° 04′ N., 70° 42′ W.) by trolling from the Woods Hole Oceanographic Institution research vessel CARYN. (Cruise C-3 under the direction of William C. Schroeder). Our recent examination of this specimen, now in the Museum of Comparative Zoology of Harvard University, has shown it to be *Parathunnus atlanticus*. This capture represents, as far as we can determine, the most northerly record for the species. On the strength of this definite record and reports of occasional catches of the species by anglers off New Jersey (related to us by Louis S. Mowbray, Director of the Bermuda Government Aquarium and Al Pflueger, Taxidermist of Miami, Florida), it seems that the concept of the northernmost limit of blackfin tuna should be changed, possibly to something like "ranging occasionally northward as far as Cape Cod."

Near the other end of its known range, one of us (Mather) found blackfin tuna quite abundant in the northwestern corner of the Caribbean in January and February of 1950. (Observation during a cruise made in the motor sailer IRMAY under charter to the Institution for Andean Research, Inc. Dr. Lionel A. Walford directed the fishery work for a portion of this cruise.) Specimens were taken and several schools were seen among the Bay Islands (16°–17° N., 86°–87° W.) and at Cozumel Island (20° 30′ N., 87° 00′ W.), and other schools believed to be the same species were sighted off the coasts of Honduras and British Honduras. Several individuals were collected and are now at the Harvard Museum of Comparative Zoology. The 21 fish taken ranged from 32 to 59 cm. in standard length, and all of those seen appeared to be within these limits.

While the species has been reported from many islands of the West Indies by Beebe and others (1928, Zoologica, 10 (1): 1–279; 1935, *Ibid.*, 19 (6): 209–24; 1936, *Ibid.*, 21 (3): 177–94) and from Courtown Key in the southwestern Caribbean by Fowler (1944, Acad. Nat. Sci. Phila., Monogr. 6: 1–583) we believe that the specimens reported here represent the first record of this tuna in the northwestern Caribbean. Furthermore, the many schools observed and the testimony of local fishermen that their presence was not unusual indicate that blackfin tuna frequent this area in considerable numbers. (This paper is Contribution No. 606 from the Woods Hole Oceanographic Institution.)—FRANK J. MATHER, III, *Woods Hole Oceanographic Institution*, AND HOWARD A. SCHUCK, *U. S. Fish and Wildlife Service, Woods Hole, Massachusetts.*

Contribution No. 607

BREVIORA

Museum of Comparative Zoology

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NOTES ON SIPHONOPHORES

3. *Nectopyramis spinosa* n. sp.

By MARY SEARS[1]

In a number of samples collected by the "Dana" in tows with 1000 to 3000 meters of wire out, there were several nectophores and bracts with rows of peculiar jagged spines (Fig. C). These spines are quite unlike those on other deep-dwelling species, such as *Vogtia pentacantha* Kölliker, *V. spinosa* Keferstein and Ehlers, and *Athorybia rosacea* Forskål. In fact, the specimens have little in common with either the Hippopodidae or the Anthophysidae. However, one nectophore was described by Moser (1925, p. 425, Pl. 25, figs. 5–7) as *Hippopodius* (?) *cuspitata*, although it actually closely resembled the specimens found in the "Dana" collection. The chief difference is that hers had the peculiar jagged spines scattered irregularly over its surface, whereas on the "Dana" specimens these are arranged in discrete rows. Nevertheless, the spines themselves seem to be identical in structure. Like the "Dana" nectophores, most of the characteristics described and figured by Moser (1925) make it appear almost certain that her specimen was also a *Nectopyramis*, not a *Hippopodius*. In all examples, the shape of the nectosac, its relation to the hydroecium, and the fact that the nectophores have all been taken singly and at considerable depths are all peculiarities of *Nectopyramis*. On the other hand, the somatocyst is tubular and not "represented by a series of divergent canals" (Bigelow, 1911a, p. 338) as defined in the brief description of the genus.

The original account was based on one species, *Nectopyramis thetis*. Soon thereafter a second species, *Nectopyramis diomedeae*, with many of the same characteristics was recorded (Bigelow, 1911b). Since then no additional species have been reported, and little more has been learned about the genus. Hence, there has been little reason for modifying the original description. Nevertheless, our ideas concerning the relationships of this genus have changed considerably. Thus, the family of the Monophyidae has been broken up and the individual genera transferred to other well-established families (Totton, 1932, p. 328) with which they had obvious affinities. *Nectopyramis*, therefore, is now referred to the Prayidae. In this family, the somatocyst and radial canals are structurally quite varied; in some, they are simple, in others branched. At first, these were used as a criterion for separating genera (Bigelow, 1911b), but more recently, a transitional form with branched radial canals and a simple somatocyst has been discovered (Leloup, 1934, p. 11). This suggests that when more is known about this family, differences in the structure of somatocyst and canals may prove to be of specific rather than generic value.

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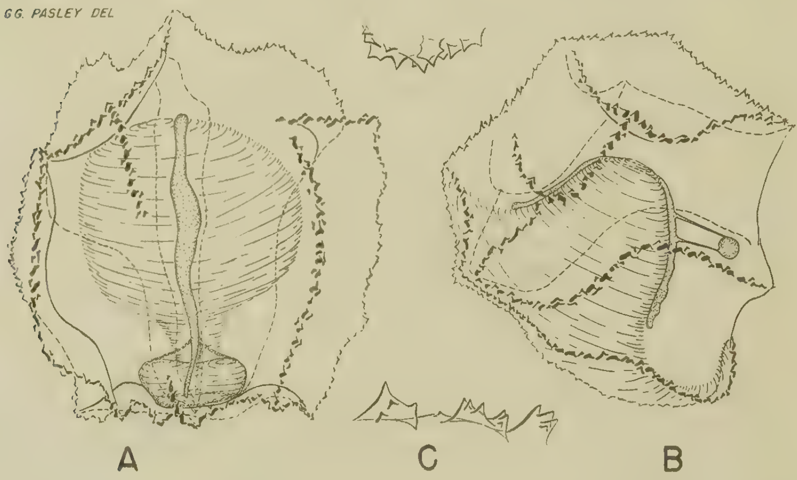
[1] Papers from the "Dana" Collection No. 38, and Contribution No. 607 of the Woods Hole Oceanographic Institution.



If, then, we consider that the shape of the somatocyst is in all probability a specific character in *Nectopyramis*, as may be the case among other prayids, we have two species originally described by Bigelow (1911a; 1911b), *N. thetis* and *N. diomedeae*, both of which had branched somatocysts, but simple radial canals and two species, *N. cuspitata* Moser and *N. spinosa* n. sp. (described below) with simple tubular somatocysts. The two latter are both spiny, but the two are readily distinguished for Moser's species is irregularly covered by the spines, but in *spinosa* these are arranged in regular rows along more or less distinct ridges.

NECTOPYRAMIS SPINOSA n. sp.

The type specimen is a nectophore about 5 mm. in length taken at "Dana" St. 3933^{IV} at 11°18′S., 50°13′E. on 20 December, 1929, in a stramin net 150 cm. in diameter towing with 2000 meters of wire out. The type specimen will be deposited in the University Museum, Copenhagen, Denmark.

Other specimens were taken as follows:

St. 3556^{II}.	2°52′N., 87°38′W. 14. IX. 1928.
S150.	2000 m. wire. 1 nectophore.
St. 3677^{IV}.	5°28′S., 130°39′E. 23. III. 1929.
S150.	2000 m. wire. 2 bracts.
St. 3920^{VI}.	1°12′N., 62°19′E. 9. XII. 1929.
S150.	1000 m. wire. 1 bract.
St. 3964^{VI}.	25°19′S., 36°13′E. 15. I. 1930.
E300.	3000 m. wire. 1 bract.
St. 3998^{III}.	7°34′S., 8°48′W. 1. III. 1930.
S150.	1000 m. wire. 1 bract.

Nectophore (Fig. A). The unique rows of jagged spines make it obvious that the nectophore is new. Although probably flattened on preservation, in dorsal or ventral view, it is roughly triangular much as are the nectophores of the other known species of *Nectopyramis*. The nectosac opens into the base of the triangle and like *N. thetis* "is comparatively small, shallow, and saucer-shaped" (Bigelow, 1911a, p. 338) with four primary radial canals along its sides. It is uncertain whether or not these eventually branch because of preservation. A large deep hydroecium lies just above it with a slit-like opening on the ventral surface. This extends the entire length of the hydroecium. The somatocyst insofar as can be determined appears to be a tubular rod extending from the base of the hydroecium to slightly above its apex. The stem and appendages are entirely missing.

Bract (Fig. B). Although bracts have not been found attached to the nectophore, there seems to be little doubt that the bracts with rows of the same jagged spines belong to this species. These are globular, about 2.5 mm. high and slightly more than 3 mm. wide. As in the nectophore, the hydroecium is so deep that it extends somewhat into the upper half of the bract. Closely associated with the hydroecium is a long tubular somatocyst which follows the outline of the hydroecium. On two of the specimens, two threadlike branches are given off dorsally and appear distally to have a globular connection.

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Contribution No. 608

DETERMINATION OF OCEAN TRANSPORTS AND VELOCITIES BY ELECTROMAGNETIC EFFECTS

By

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ABSTRACT

The electric potentials in and about an ocean current are shown to be related in a simple fashion to the total fluid transport. In many waters, surface measurements alone permit the determination of this total transport. It is also established that the local vertical potential gradient is a measure of the local velocity. Several techniques of measurement, including the "Geomagnetic electrokinetograph" method, and the errors which may be involved in each, are discussed.

INTRODUCTION

In reinvestigating[2] the electric potentials induced in ocean currents by the magnetic field of the earth, this work determines the relation between the total potentials across the current and the total volume transport of fluid.[3] The validity of interpreting local electric effects as indicative of the local velocity structure of the fluid stream is discussed, and thus the usefulness of the vertical potential gradient for this purpose is established. Though various methods of measurement are possible, the measurements from shipboard are stressed. A ship moving with the fluid stream, however, induces an additional potential; hence an analysis of the relation between shipboard measurement and velocity structure is made for both magnetic field components.

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[1] Contribution No. 608 from the Woods Hole Oceanographic Institution.

[2] Previous work has included the papers of: Faraday (1832); Longuet-Higgins (1949); Stommel (1948); von Arx (1950).

[3] Kolin (1945) and Arnold (1951), among others, have arrived at similar relations for the flow of fluid in a pipe.

In this paper, (I) the relations between the total transports and electric potentials are deduced and the approximations involved in relating local electric observables to local velocities are determined, and (II) the limitations imposed by the techniques of measurement are discussed and possible future experiments are suggested.

DISCUSSION

I. It will be recalled that the motion of a conductor at right angles to a magnetic field produces an electric field whose magnitude is $V \times H \times 10^{-8} \dfrac{\text{volts}}{\text{cm}}$ and which is at right angles to both the motion and the magnetic field (where V is the velocity of the conductor and H the magnetic field). Therefore, as a result of its motion relative to the earth's magnetic field, an ocean stream will have a certain electromotive force induced in it at every point. These emf's set up electric currents and electric fields, and at every point in the fluid the electric current density is proportional to the *effective* electric field and the conductivity of the medium. That is to say,

$$\rho \boldsymbol{i} = \boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{H}, \tag{1}$$

where ρ = resistivity of the water, $\boldsymbol{V}$ = vector velocity of the water, $\boldsymbol{H}$ = earth's magnetic field, $\boldsymbol{i}$ = electric current density, and $\boldsymbol{E}$ = electric field vector.

It is assumed first that the electric and magnetic forces on the ions in the sea are small compared to the hydrodynamic forces, that the electric currents which flow do not appreciably alter the earth's magnetic field, and that a steady state exists. Then the electric field may be represented by a potential function φ, $E = -\nabla\varphi$ (since $\nabla \times \boldsymbol{E} = 0$). Hence

$$\nabla\varphi = \boldsymbol{V} \times \boldsymbol{H} - \rho \boldsymbol{i}, \tag{2}$$

or

$$\frac{\partial\varphi}{\partial x} = (V_y H_z - V_z H_y) - \rho i_x\,, \tag{3}$$

$$\frac{\partial\varphi}{\partial y} = (V_z H_x - V_x H_z) - \rho i_y\,, \tag{4}$$

$$\frac{\partial\varphi}{\partial z} = (V_x H_y - V_y H_x) - \rho i_z\,, \tag{5}$$

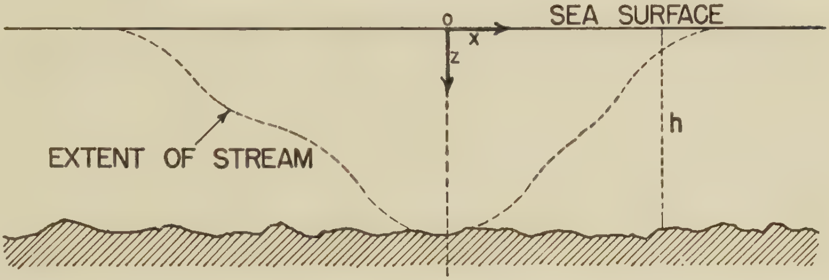

Figure 1.

where the subscripts x, y, z denote the components of velocity, magnetic field, and electric current in those directions.

Now one considers a coordinate frame with the y-axis (into the paper) along the mean direction of an ocean stream, as in Fig. 1. The total surface integrals of equations (3) and (5) to a constant depth z in the x, z plane may be written as

$$\int_{-\infty}^{+\infty}\int_{0}^{z} \frac{\partial\varphi}{\partial x}\,dx\,dz = \int_{-\infty}^{+\infty}\int_{0}^{z} \Big[(V_y H_z - V_z H_y) - \rho i_x\Big]\,dx\,dz\,, \qquad (6)$$

and

$$\int_{-\infty}^{+\infty}\int_{0}^{z} \frac{\partial\varphi}{\partial z}\,dx\,dz = \int_{-\infty}^{+\infty}\int_{0}^{z} \Big[(V_x H_y - V_y H_x) - \rho i_z\Big]\,dx\,dz\,. \qquad (7)$$

In actual ocean streams $\int_{-\infty}^{+\infty}\int_{0}^{z} V_z H_y\,dx\,dz$ is very much smaller than $\int_{-\infty}^{+\infty}\int_{0}^{z} V_y H_z\,dx\,dz$ except on the magnetic equator, while $\int_{-\infty}^{+\infty}\int_{0}^{z} V_x H_y\,dx\,dz$ is very much smaller than $\int_{-\infty}^{+\infty}\int_{0}^{z} V_y H_x\,dx\,dz$ except in the rare situation where H_x falls to zero. Partially integrating the potential gradients in equations (6) and (7), one obtains

$$\int_{0}^{z} [\varphi(\infty, z) - \varphi(-\infty, z)]\,dz = \int_{-\infty}^{+\infty}\int_{0}^{z} H_z V_y\,dx\,dz - \int_{-\infty}^{+\infty}\int_{0}^{z} \rho i_x\,dx\,dz, \qquad (8)$$

and

$$\int_{-\infty}^{+\infty} [\varphi(x,0) - \varphi(x,z)]\,dx = \int_{-\infty}^{+\infty}\int_{0}^{z} H_x V_y\,dx\,dz - \int_{-\infty}^{+\infty}\int_{0}^{z} \rho i_z\,dx\,dz\,. \qquad (9)$$

Since the electric current has no sources or sinks (i. e., $\nabla \cdot \rho \mathbf{i} = 0$), there can be no net flow across any infinite line (plane); therefore

$$\int_{-\infty}^{+\infty} \rho i_z \, dx = \int_0^{\infty} \rho i_x \, dz = 0 \, .^4$$

Hence the last term in equation (9) is always zero, so that

$$\int_{-\infty}^{+\infty} [\, \varphi(x, 0) - \varphi(x, z)] \, dx = \int_{-\infty}^{+\infty} \int_0^z H_z \, V_y \, dx \, dz \, ,$$

and if H_z has small spatial variation across the stream, one may write

$$\oint \varphi dx = H_x T_z \, , \tag{10}$$

where $\oint$ denotes integration around an infinite rectangular contour bounded by $z = 0$ and any other arbitrary z, and where T_z is the total volume transport of fluid through that contour. Note that this result is independent of the depth of the sea or of bottom conductivity. The last term in equation (8) is not zero in general, but in the case of a nonconducting bottom, $\int_0^h \rho i_x dz = \int_0^{\infty} \rho i_x dz = 0$, since no current flows below $z = h$; hence

$$\int_0^h [\varphi(\infty, h) - \varphi(-\infty, h)] \, dz = \int_{-\infty}^{+\infty} \int_0^h H_z \, V_y \, dx \, dz \, .$$

Since, at some large distance from the stream, φ does not vary with depth, the relation above may be rewritten as

$$(\varphi_{+\infty} - \varphi_{-\infty}) = \frac{H_z T}{h} \, , \tag{11}$$

where H_z is again assumed to have small spatial dependence, T is the total volume transport of fluid, $\varphi_{+\infty} - \varphi_{-\infty}$ is the total potential difference across the stream, and h is the mean depth of the bottom. Estimates of the effect of bottom conductivity in reducing $\varphi_{+\infty} - \varphi_{-\infty}$ have been made by using a three layer analysis developed by Stommel

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[4] The electric current in the y direction has been neglected in this equation in comparison with i_x. This corresponds to the observation that

$$\int_{-\infty}^{+\infty} \int_0^z V_x H_y dx \, dz \ll \int_{-\infty}^{+\infty} \int_0^z V_y H_x d \quad dz$$

and is an approximation of the same magnitude.

(1948); they indicate errors of less than 1% at a few kilometers from the edge of the stream for bottom conductivities one thousandth that of the sea's.

Before discussing the actual measurements made by a ship, several relations permitting interpretation of local velocities will be discussed.

Returning to equation (5) and neglecting again the small term due to V_x, note that $\rho i_z = 0$ at the surface of the sea and $\rho i_z \approx 0$ at the sea bottom. In fact, determination of ρi_z for various model streams similar to those in nature indicate that it is never more than a few percent of $V_y H_x$.

Hence

$$\frac{\partial \varphi}{\partial z} = - V_y H_x ,$$

or

$$V_y = - \frac{1}{H_x} \frac{\partial \varphi}{\partial z} . \tag{12}$$

The approximations involved in this useful equation seem small compared to the possible errors in measurement to be discussed in Section II.

A second approximate relation involves a definition of a quantity

$$k = \frac{H_z V_y}{\rho i_x} . \tag{13}$$

Previous authors (von Arx, 1950; Stommel, 1948) have shown that k is related to the average "equivalent" depth near the region of observation, i. e.,

$$k \approx \frac{h}{h - h_1} ,$$

where h_1 is a depth such that $V_y(x, 0)\ h_1$ is the transport per unit section of the stream at the point x. Differentiating equation (8) with respect to z one obtains

$$(\varphi_{+\infty} - \varphi_{-\infty}) = \int_{-\infty}^{+\infty} H_z\, V_y\, dx - \int_{-\infty}^{+\infty} \rho i_x\, dx$$

$$= \int_{-\infty}^{+\infty} \rho i_x (k - 1) dx = \frac{H_z T}{h} . \tag{14}$$

Hence a point to point knowledge of k and ρi_x permit the determination of the total transport, while

$$V_y \approx \frac{\rho i_x}{H_z} \tag{15}$$

if k is quite close to one, as it may be in equatorial currents.

Another defined quantity,

$$K = \frac{\int_{-\infty}^{+\infty} H_z V_y dx}{\int_{-\infty}^{+\infty} \rho i_x dx}, \tag{16}$$

also has proved to be quite useful. From equations (8) and (11)

$$\varphi_{+\infty} - \varphi_{-\infty} = \frac{H_z T}{h} = (K - 1) \int_{-\infty}^{+\infty} \rho i_x dx, \tag{17}$$

and, since K is the ratio of two integrals, the local random errors and fluctuations of the observations of V_y and ρi_x are smoothed out. Perhaps a more significant aspect of K is its relation to the mean depth of the total fluid stream. Hence K may be a constant or near-constant for a particular section of the stream, or it might be deduced from theoretical relations between the horizontal and vertical velocity profiles.

A cable laid on or anchored to the ocean bottom could directly measure the potentials in the preceding relations. A ship, however, induces an additional potential between any electrodes it may tow due to its own motion. Considerable discussion has been given to the problems of electrodes towed in line behind a ship (von Arx, 1950). In the absence of wind drift at right angles to the electrodes' heading, the measured potential gradient is

$$(\nabla\varphi)_{measured} = \nabla\varphi - \boldsymbol{V} \times \boldsymbol{H} = -\rho\boldsymbol{i}. \tag{18}$$

Since the total potential across the stream is

$$\int_{-\infty}^{+\infty} \nabla\varphi \cdot d\boldsymbol{l} = \int_{-\omega}^{+\infty} (\boldsymbol{V} \times \boldsymbol{H} - \rho\boldsymbol{i}) \cdot d\boldsymbol{l} \qquad \text{(measured at surface)}$$

where $d\boldsymbol{l}$ is the increment of path of the ship as it crosses the stream, a navigational determination of this path can provide the integral $\int_{-\infty}^{+\infty} \boldsymbol{V} \times \boldsymbol{H} \cdot d\boldsymbol{l}$; this knowledge, plus the measured potential, provides $\int_{-\infty}^{+\infty} \rho\boldsymbol{i} \cdot d\boldsymbol{l}$. The total fluid transport is then found from equations (11) or (17).

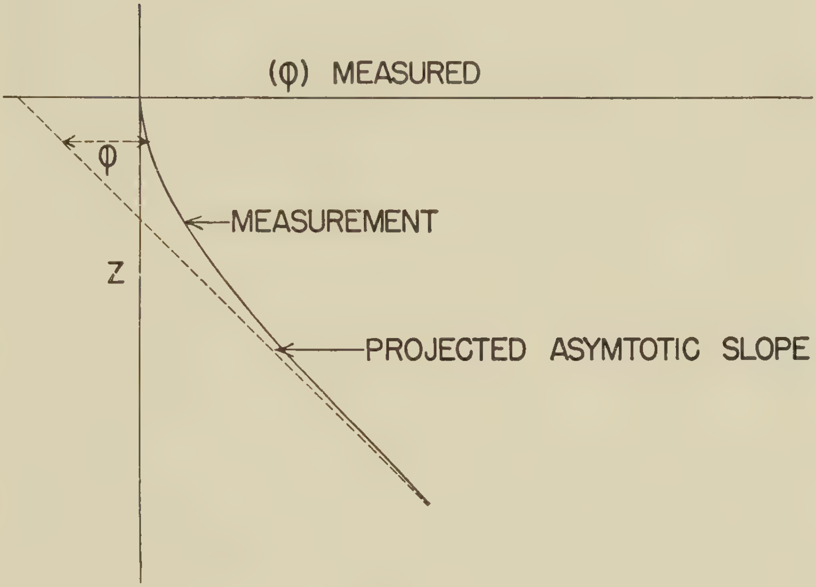

Figure 2.

For an electrode which is let down from a ship to determine the potential between a surface electrode and depth *z*,

$$\varphi_{measured} = \boldsymbol{V_B} \times \boldsymbol{H} \cdot \boldsymbol{s} - \int_0^s \nabla\varphi \cdot d\boldsymbol{s}\,, \qquad (19)$$

where $\boldsymbol{s}$ is the vector distance between the surface and deep electrode and $\boldsymbol{V_B}$ is the velocity of the ship with respect to the earth. In the simple case of the ship drifting or moving such that the deep electrode departs only slightly from due upstream or due downstream in its horizontal displacement from the surface electrode, the measured potential becomes:

$$\varphi_{measured} = V_B \times \boldsymbol{H} \cdot \boldsymbol{z} - [\varphi(x, z) - \varphi(x, 0)]\,. \qquad (20)$$

(One assumes that the depth z can be determined from the pressure at the deep electrode.) The gradient of $(\varphi)_{measured}$ permits the determination of $[V_B - V_y\,(x, 0)]$ as well as the variation of V_y with depth from equation (12), and, if the measurements are made to sufficient depth to be below the stream (i. e. $\frac{\partial\varphi}{dz} \rightarrow 0$), then $V_y\ (x,\ 0)$ and V_B separately are determined. Fig. 2 shows a theoretical measurement from a drifting ship and may help to clarify these conclusions.

φ, the potential at depth z, is the potential between the measured curve and the projection of its asymptotic slope. The initial slope of $(\varphi)_{measured}$ for a drifting ship is zero, as indicated, while the initial slope for a moving ship determines $[V_B - V_y(x, 0)]$.

II. The difficulties encountered in measuring the potential differences induced by the motion of the sea seem to have two main sources. The first is the changing electrochemical potentials which exist between even the most carefully chosen electrodes and the electrochemical potentials in the sea due to spatial variation in the temperature, salinity and oxygen content. The second is the navigational error in determining the change of ship position with time. A third and seemingly less important difficulty is the error in estimating the wind drift of the ship.

The magnitude of these errors has been analyzed in considerable detail in previous publications, e. g. von Arx (1950), and those computations are borne in mind here in discussing measurements based on equations (10), (11), and (12).

From equation (11) the total transport may be determined by surface measurements alone, and hence the electrochemical problem of spatial variation of physical properties is minimized. However, the difficulty of determining surface velocities from navigational measurements is exaggerated by the subtraction of $\int_{-\infty}^{+\infty} \rho \boldsymbol{i} \cdot \boldsymbol{dl}$ from $\int_{-\infty}^{+\infty} \boldsymbol{V} \times \boldsymbol{H} \cdot \boldsymbol{dl}$, for both of these experimental quantities may be large, while their difference, proportional to the total transport, may be small in comparison. A criterion for the usefulness of equation (11) is K, defined in equation (16) as

$$K = \frac{\int_{-\infty}^{+\infty} \boldsymbol{V} \times \boldsymbol{H} \cdot \boldsymbol{dl}}{\int_{-\infty}^{+\infty} \rho \boldsymbol{i} \cdot \boldsymbol{dl}}.$$

The probable error is then at least $\frac{1}{K - 1}$ greater than the integrated navigational error. (Preliminary surveys of the Gulf Stream area [von Arx, 1951] suggest that K lies in the range of 1.1 to 1.5. Equatorial waters may be expected to have small K's, and since there is no Loran network in these areas, the usefulness of equation [11] would be small.)

From equations (10) and (12) one might deduce both local velocities and total transport in all waters, yet here the electrochemical problem is most serious. While the determination of temperature with depth can easily be made and corrections to the observed potential established, the variation of oxygen with depth can produce potentials considerably in excess of those due to the fluid transport. Several suggestions have been advanced to shield the electrodes from these concentration gradients. Surrounding the deep electrode with water carried from the surface seemed the most feasible of these, but no assurance of the success of this method can be given until adequate experiments have been performed.

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The slopes of cumulus clouds in relation to external wind shear

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SUMMARY

An equation for the slope of cumulus clouds is derived. It is shown to depend upon the vertical ascent rate, the external wind shear and the horizontal frictional forces between the cloud and its surroundings. These frictional forces are of two origins : one due to entrainment or mixing with the outside air, and the other due to form or body drag.

Four observational cases are presented, one concerning trade cumulus, and three involving clouds in mid-latitudes. In two of these, measurement of updraught speed, wind shear, and cloud slope permit an estimate of the magnitude of the friction forces. The minimum contribution due to entrainment is approximately equal to that inferred by Stommel for trade cumulus.

1. INTRODUCTION

The effect of wind shear upon the dynamics of convection requires attention in the degree that interaction between convective elements and the surrounding air is recognized. In recent years sufficient observational evidence has been gathered to shed doubt upon the adequacy of models based upon the non-interacting parcel. The manner in which these observations depart from parcel-method predictions is in itself suggestive of a direction in which modifications may be attempted. Lapse rates inside convective clouds have been found to be *greater* than moist adiabatic and to fluctuate irregularly with height; observed temperature excesses and updraught strengths have been smaller than if the cloud air followed the moist adiabat ascribed to it by parcel considerations; cloud tops have *ceased* growing when vast amounts of ' positive area ' were available; and liquid-water content has been often found to be only a fraction of that expected.

The first important step toward a cloud model possessing these features was made by Stommel (1947). He showed that the lapse rates found in several examples of trade cumuli could be accounted for if an amount of outside air were entrained into or mixed with the rising cloud. Such entrainment would constitute an interaction between cloud and surroundings by which some of the momentum, vapour content, and heat of the environment is imparted to the cloud, thus creating a resistance to its growth. Studies succeeding Stommel's have shown that if entrainment or mixing does occur to the magnitude that he inferred, a consistent picture of cumulus convection is possible which possesses the observed departures from the parcel model.

Owing to the difficulties of measurements within clouds, however, many meteorologists have been awaiting more definite evidence of the occurrence and magnitude of cloud-environment interaction. The slope of a cumulus is recordable with the simplest camera, and can be used in conjunction with wind profiles to supply an independent determination. Evaluation of the resistance forces on updraughts is therefore the primary objective of this paper on cloud slopes. An additional and corollary objective is to predict and verify a quantitative relation between cloud slant and wind shear and by means of the model so constructed to explain the well-known observation that under equal stability and moisture conditions a strongly slanting cloud is less likely to reach great heights than one which grows more nearly vertically.

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2. Theory

The slope of an updraught (whether there are condensed water droplets in it or not is, for the moment, unimportant) at any level depends only upon the ratio of its vertical ascent rate to the departure of its horizontal velocity at that level from that at its base, namely,

$$\tan \theta = \text{slope} = \frac{w}{u_c - u_{E_0}} \quad . \quad . \quad . \quad . \qquad (1)$$

where the horizontal coordinate, x, is chosen in the plane in which the slope is to be determined and is taken positive in the direction of the component in this plane of the wind at draught base. The angle θ is measured in degrees counterclockwise from the positive x-axis. The vertical draught speed is w; the horizontal speed of the draught air in the x-direction is u_c, and its horizontal speed at its base is u_{E_0}, or the speed of the external wind.

(*a*) *Determination of the horizontal speed of the air in an updraught*

If a rising body has very great inertia relative to the forces exerted on it by the surrounding air, then it will retain most of its initial horizontal velocity, undergoing little deflection. The parcel method implies that convective elements belong to this category, and therefore that the slant of cumulus clouds should be negligible (i.e., $\theta \simeq 90°$). If, however, a rising body such as a pilot balloon has relatively small inertia its horizontal velocity will approximate that of the air through which it is passing, and the slant of its upward path will be a maximum. Observations discussed by Malkus (1949) and Byers and Braham (1949) show that the behaviour of a rising cumulus lies between these extremes.

The nature of the drag forces operating on cumulus has been described by Schmidt (1947). There are essentially two ways in which a rising air bubble or column exchanges horizontal momentum with its surroundings. The first is due to entrainment into the draught of a portion of the outside air, and the second, to the draught's pushing air aside and around itself, creating a ' countercurrent ' in the horizontal by means of a pressure difference across its boundaries. This latter force has been called ' form ' or ' body ' drag. In the original work predicting the magnitude of cloud-air velocities, entrainment was considered as the only frictional force, and it was assumed that all the entrained air was carried along with the updraught. However, clouds or thermals apparently maintain an approximately constant cross section with height and observations (especially time-lapse motion pictures, but also some airplane traverses through clouds reported on by Malkus 1949) suggest that some of the cloud air is detrained, so that the draught retains roughly only that fraction of the influx required to preserve continuity without significantly expanding its cross-sectional area (see discussions by Austin 1951, and Malkus 1952). The following derivation of an expression for the horizontal draught velocity is somewhat more realistic and general than the previous work in that it can include form drag and detrainment.

In the present model, as in those preceding it (Stommel 1947, Malkus 1949), an updraught in a steady state is considered. The rising air is assumed to be well mixed, homogeneous, and discontinuously distinct from its surroundings. A form of Newton's second law of motion is applied to a small vertical segment of the updraught between the levels z and $z + dz$. An x-z slice is schematically illustrated in Figure 1. At z the upward mass flux across the entire rising column is M g/sec; its speed in the

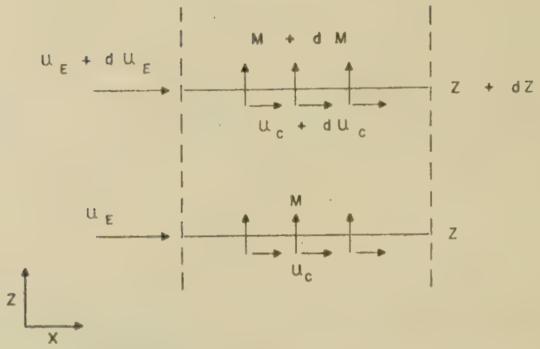

Figure 1. Schematic vertical cross section through a homogeneous updraught. M is the upward mass flux through level z; u_c is the x-component of the horizontal draught speed; u_E is the x-component of the external wind. At the level $z + dz$, these have become $M + dM$, $u_c + du_c$ and $u_E + du_E$, respectively. The boundaries of the draught are indicated by dotted lines since they in no way act as walls; nor need the cross-sectional area remain constant. The change in momentum flux between level z and $z + dz$ is considered in the theory.

x-direction is u_c cm/sec; and the x-component of the external wind is u_E cm/sec. At $z + dz$, the upward mass flux in the updraught has become $(M + dM)$ g/sec where dM is the net increase of flux brought about by entrainment. The speed of the draught in the x-direction is $(u_c + du_c)$ cm/sec; and the x-component of the external wind is $(u_E + du_E)$ cm/sec. The net increase in flux due to entrainment, dM, can be expressed as follows :

$$dM = dM_i - dM_0 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where dM_i would be the increase in flux if all entrained air were retained and dM_0 is the flux of draught air lost by detrainment.

The momentum-flux equation for the segment is therefore

$$d\,(Mu_c) = u_E\,dM_i - u_c\,dM_0 + fdz \quad . \quad . \quad . \quad (3)$$

where the left side of the equation represents the increment of horizontal momentum flux in the draught between z and $z + dz$, and the right side may be regarded as the sum of the forces acting. The first two terms on the right represent the changes of momentum flux due to entrainment, and the third term is the form-drag force where f represents the force per unit height upon the rising column.

If Eq. (3) is expanded, divided through by M and dz, and relation (2) is used, it becomes

$$\frac{du_c}{dz} + (u_c - u_E)\,\frac{1}{M}\,\frac{dM_i}{dz} = \frac{f}{M} \quad . \quad . \quad . \quad (4)$$

This equation for u_c as a function of z can be integrated if the functional dependence upon z of M_i, M, u_E and f is known.

In general, observations of the latter quantities are, at best, only available at distinct levels. At this stage, therefore, the simplicity of integrating the equation by steps is justified, assuming for the interval Δz from one measurement to the next that

$$u_E = u_{E_0} + bz \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$\frac{1}{M}\,\frac{dM_i}{dz} = \overline{\frac{1}{M}\,\frac{dM_i}{dz}} \equiv P = \text{const.} \quad . \quad . \quad . \quad (6)$$

and

$$\frac{f}{M} = \frac{f}{\bar{M}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where $\bar{M}$ is the average mass flux in the draught in the height interval Δz and P is the fraction of its average mass flux exchanged per unit height between draught and environment. It is clearly the gross entrainment, $\frac{1}{M}\frac{dM_i}{dz}$, or total amount of outside air mixed with the cloud, which is calculated by the Stommel method of comparison between cloud and environment soundings and his results indicate that P is of the order of magnitude of 10^{-5} cm^{-1}.

(*b*) *The form drag*

Rather little is known at present concerning the form drag on clouds. It seems probable that its horizontal component might resemble and possibly be of the same order of magnitude as the drag on a solid cylinder of comparable size moved at comparable speed through the air.

Aerodynamicists give the form drag force per unit height on the cylinder in air as

$$F = C_D \frac{\rho u^2 d}{2} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where ρ is the air density, d the cylinder diameter, u the velocity of the cylinder relative to the air, and C_D the dimensionless ' drag coefficient.' Experimentally, this coefficient is found to depend upon the Reynolds number, or the extent to which turbulence around the cylinder is developed. For Reynolds numbers in the range 10^5 to 10^6, C_D for solid cylinders drops abruptly from a fairly constant value of about 1·5 to about 0·3 at the point where the boundary layer becomes turbulent and thereby clings more closely, giving a more restricted wake. The Reynolds number for clouds is about 10^8 to 10^9, so that C_D might be expected to be about 0·3. However, what the behaviour of the boundary layer will be in the case of an air ' cylinder ' moving through air, where mixing at the boundary is continually occurring, is probably impossible to predict without experiments. In any case, it seems unlikely that the form drag on a cloud could exceed that on a comparable solid cylinder when the higher drag coefficient is used. For draughts of diameter 1 km, moving through the air at 2 m/s, Eq. (8) gives a form-drag force ranging between $0{\cdot}7 \times 10^6$ to $3{\cdot}6 \times 10^6$ dynes per cm of vertical extent for a C_D between 0·3 to 1·5. The force due to normally developed entrainment for such a draught rising at a few m/sec lies roughly in this range also. Since some of the environment air is moving ' through ' the draught rather than around it, the solid cylinder drag may be expected to set an upper limit for the form-drag term. A rough calculation made for the same draught as that of the previous example shows that entrainment and detrainment may move a mass of air through the draught per second of comparable magnitude to that displayed by it. Therefore the form-drag term may range from totally negligible up to equal magnitude with the force due to entrainment.

In view of the above discussion an expression for f proportional to $(u_E - u_c)^2$ should be substituted into Eq. (4). This has been done and the solution to the resulting non-linear equation has been obtained. From that solution it is readily shown that for reasonable values of the friction forces and other parameters, only very small differences in u_c result in the first km or more above cloud base between an f of the quadratic form and an f linearly dependent on $(u_E - u_c)$, namely,

$$f = Q'(u_E - u_c) \qquad . \quad . \quad . \quad . \quad . \qquad (9)$$

where Q' is adjusted so that Eq. (9) gives the same friction force as the non-linear expression at cloud mid-level. It is probably worth sacrificing slight refinements in the form-drag term for this simplification, since so very little is known about form drag on convective draughts at present that even an estimation of its order of magnitude would represent a significant step.

(*c*) *Solution of the equation*

Upon substitution of Eqs. (6), (7), and (9) into Eq. (4) it becomes

$$\frac{du_c}{dz} = (u_E - u_c)\,P + Q\,(u_E - u_c) \qquad . \quad . \quad . \qquad (10)$$

where $Q = Q'/M$. A tentative expression to estimate the order of magnitude of Q may be derived from combination of its definition with Eqs. (8) and (9). It states that

$$Q = \frac{2C_D\,(u_E - u_c)}{\pi\, d\, w} \qquad . \quad . \quad . \quad . \qquad (11)$$

If now du_E/dz is subtracted from both sizes of Eq. (10) and $(u_E - u_c)$ is called v, Eq. (10) simplifies to

$$-\frac{dv}{dz} = (P + Q)\,v - b \qquad . \quad . \quad . \quad . \qquad (12)$$

when relation (5) is also introduced.

The solution of Eq. (12) is readily found to be

$$c\,(Rv - b) = e^{-Rz} \qquad . \quad . \quad . \quad . \qquad (13)$$

where c is the constant of integration and $R = P + Q$. It is easily shown that equal form drag and entrainment frictional forces give equal P and Q. The most general boundary condition for evaluation of c states that at some level l above draught base $(u_E - u_c) = (u_E - u_c)_l = v_l$. Therefore, from this level upward

$$v = (u_E - u_c) = \frac{b}{R}\left[1 - e^{-R(z-l)}\left(1 - \frac{R}{b}\,v_l\right)\right] \qquad . \quad . \qquad (14)$$

By successive applications of Eq. (14) the relative cloud-air horizontal velocity can be determined for the entire vertical extent of a draught. From its base up to the first level where R or b changes, the equation has a particularly simple form, since if $l = 0$, $v_l = 0$.

The cloud slope can finally be written

$$\tan\theta = \frac{w}{(u_c - u_{E_0})} = \frac{w}{b\left[z + \dfrac{1}{R}\,(e^{-Rz} - 1)\right]} \qquad . \quad . \qquad (15)$$

when average values of b and R are taken. It is readily obtained and only slightly more complicated when R and b change at one or more upper levels.

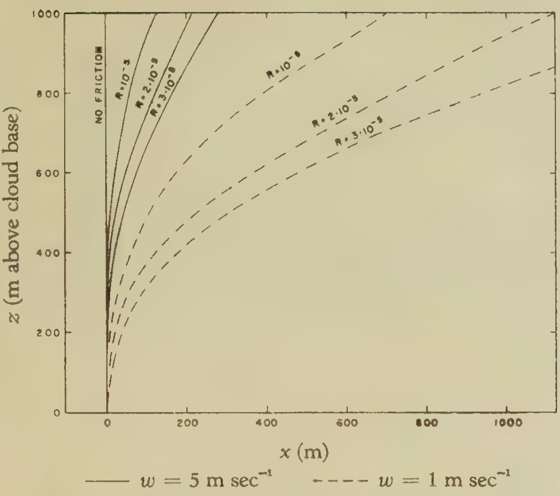

Figure 2. Horizontal draught displacements as a function of height for varying vertical speeds and friction forces when the wind shear is 5 m sec^{-1} km^{-1}. Calculation made from Eq. (15).

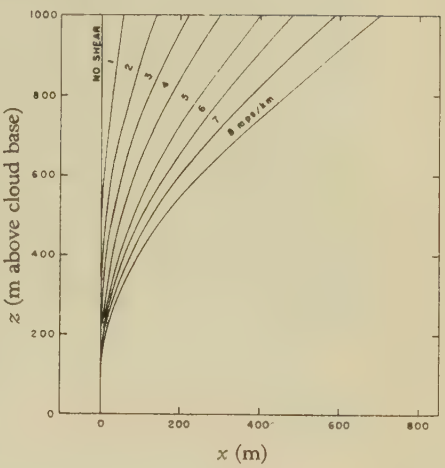

Figure 3. Horizontal draught displacements as a function of height for varying wind shears when the ascent rate is 3 m sec^{-1} and the friction coefficient $R = (P + Q)$ is 2×10^{-5} cm^{-1}. Since the slant varies inversely as w, these curves would each correspond to one-half the shear when w is halved, etc. Calculation made from Eq. (15).

It is seen immediately from Eq. (15) that the model predicts clouds which slant in the postive x or forward direction when the x-component of the wind increases with elevation, and backwards when the wind decreases upward, the slant increasing in direct proportion to the shear. Moreover as long as the cloud remains in a steady state and its updraughts are neither strengthening nor weakening with time, *the slope remains constant*. The fact that real clouds are observed to become more slanting with time is due to the gradual weakening of their updraughts and is discussed presently. Eq. (15) shows that the slant increases linearly as w decreases, if one assumes roughly that the decay can be represented by a series of quasi-steady states of smaller and smaller w.

Figs. 2 and 3 show sample calculations made from Eq. (15). Fig. 2 takes a constant, moderately large external shear of 5 m sec^{-1} km^{-1}. The slopes of the clouds are then predicted for varying total average frictional forces and mean vertical speeds. For equal shear and vertical speed, the increase of cloud slant with increased friction is found to be sub-linear, the more so the larger the frictional forces. However, since increased horizontal friction of the type due to entrainment, at least, implies increased resistance to vertical cloud growth and hence reduced upward speeds, the slope in real clouds may depend far more sensitively on R (via P) than would appear from first glance at Fig. 2. Also, real clouds will slant more near their bases than the theoretical clouds because there the vertical velocities will be smaller than in their central portions.

Fig. 3 shows the effects of normally observed wind shears on cumulus having vertical speeds of 3 m/sec – of the order found in swelling cumulus in mid-latitudes and probably in most trade cumulus (see Stommel 1951). Shears in the trade-wind cloud layer usually range from 1 m sec^{-1} km^{-1} to 3 m sec^{-1} km^{-1}, while in the corresponding layer in mid-latitudes they average 5 m sec^{-1} km^{-1} to 7 m sec^{-1} km^{-1}. Trade cumuli, then, for the same vertical speeds may be expected to slant considerably less than their mid-latitude counterparts.

(*d*) *Effect of slant upon cloud dynamics and life cycles*

It has been shown by the *Thunderstorm Project* (see Byers and Braham 1949, Chap. V) that cumulonimbus clouds grow by putting up successive towers at or near their tops. Observations presented in the next section show that smaller cumulus also behave in this manner. If the wind shear is weak, the cloud turrets will remain nearly vertical even as their upward velocities decay and they dissipate. The new turrets can then grow into and entrain air moistened by their predecessors. When, on the other hand, the external shear is strong, the dissipating towers become very strongly slanting and the new vigorous towers, which grow much more nearly vertically, are penetrating dry air. To obtain a quantitative idea of this effect, reference is made to Fig. 3. If the external shear is, for example, 1 m $\sec^{-1}$ km^{-1}, the slant of the tower increases from that of the line marked '1' to the line marked '2' as the vertical velocity decreases to $1\frac{1}{2}$ m $\sec^{-1}$. The slant has only increased to that of the line marked '4' when the cloud is in such an advanced stage of dissipation that its ascent rates are only 75 cm/sec. If, in contrast, the shear is 6 m $\sec^{-1}$ km^{-1}, the tower slants along the line marked '6,' reaching '8' when the updraught speed has only declined to $2\frac{1}{4}$ m $\sec^{-1}$. This example illustrates one of the several reasons why trade cumuli grow so readily, day and night, with smaller turbulence and perhaps less required buoyancy for given vertical speeds compared to their mid-latitude counterparts.

The model just presented may also be used to calculate the frictional forces on clouds from their observed slopes. If a mean vertical velocity at several levels were known, as well as the external wind shear, the friction forces could be calculated, level by level, from photographs showing cloud slope. If, in addition, temperature and wet-bulb readings were available inside and outside the cloud at these same levels, one would have all the information necessary to calculate gross entrainment by Stommel's method, the net entrainment to fulfil continuity, the total horizontal friction force from the slope, and the horizontal form-drag force from the difference between the entrainment force and the total horizontal friction force. Unfortunately, such simultaneous data are so far lacking. Various less complete sets of observations are however, available, and are sufficient for qualitative verification of the foregoing predictions and to suggest further lines of investigation.

3. OBSERVATIONS

(*a*) *First case – an example of trade cumulus.* Fig. 4 (Plate III) shows a photograph of oceanic trade cumuli in the region of San Juan, Puerto Rico, on the afternoon of 25 Apr. 1946. It was taken by the Wyman-Woodcock (Woods Hole Oceanographic Institution*) Caribbean expedition from an altitude of about 18,000 ft. The wind (from ESE.) blows from left to right in the plane of the picture and decreases upwards. The clouds clearly slope backwards, in qualitative agreement with Eq. (15). Fortunately, temperature and wet-bulb soundings were made inside and outside one of the clouds in the area. The gross entrainment and vertical velocities in this cloud have been calculated from the soundings by Stommel (1951) and are reproduced in Table I, along with the present calculations.

In computing these vertical velocities, Stommel assumed, among other things, that the entrainment calculated from the soundings was the only resistance force

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* Sponsored by the U.S. Navy's Bureau of Ships and Office of Naval Research. Reported on by Bunker, Haurwitz, Malkus and Stommel (1949)

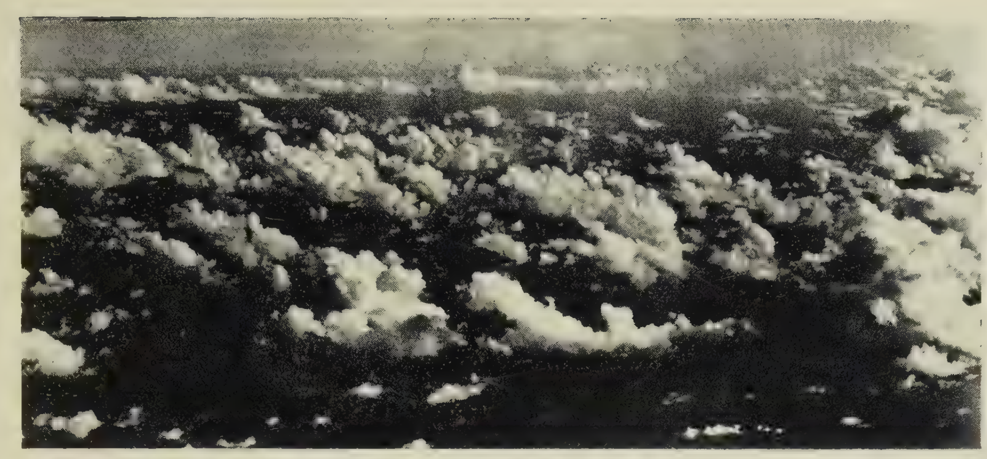

Figure 4. Photograph of trade cumulus north-east of Puerto Rico (20°00′N, 64°25′W) on the afternoon of 25 Apr. 1946 taken from 18,000 ft altitude. The camera was pointed toward a direction just west of south, at right angles to the ESE. wind, which decreases upwards. The wind therefore blows from left to right across the photograph. The soundings discussed in the text were made within and near one of the clouds in the area. Cloud base is at about 600 m, tops about 1,200 m to 1,400 m.

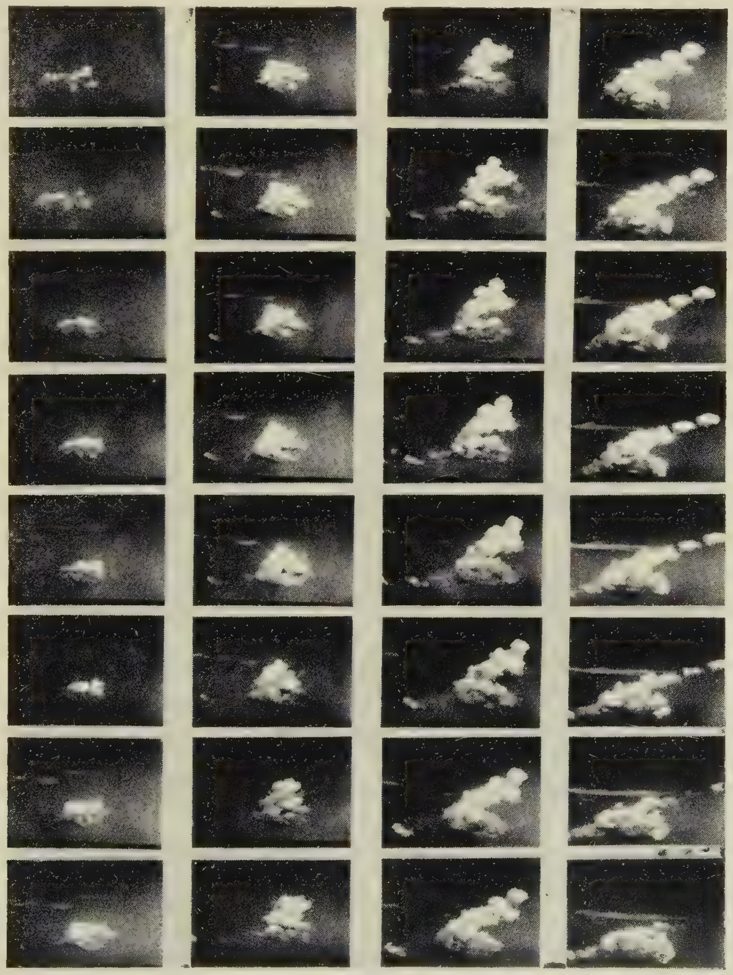

Figure 6. Sequence showing the life history of a cloud turret over Nantucket Island (Massachusetts, U.S.A.) on 14 Aug. 1950. Frames are reproduced every 30 secs, beginning in the upper left. The horizon is visible as a dark line in the foreground. The camera was pointed nearly due east, at right angles to the surface wind which was from the south (right), decreasing rapidly upward. Cloud base was at 450 m and the highest level reached by the top was just over 2 km.

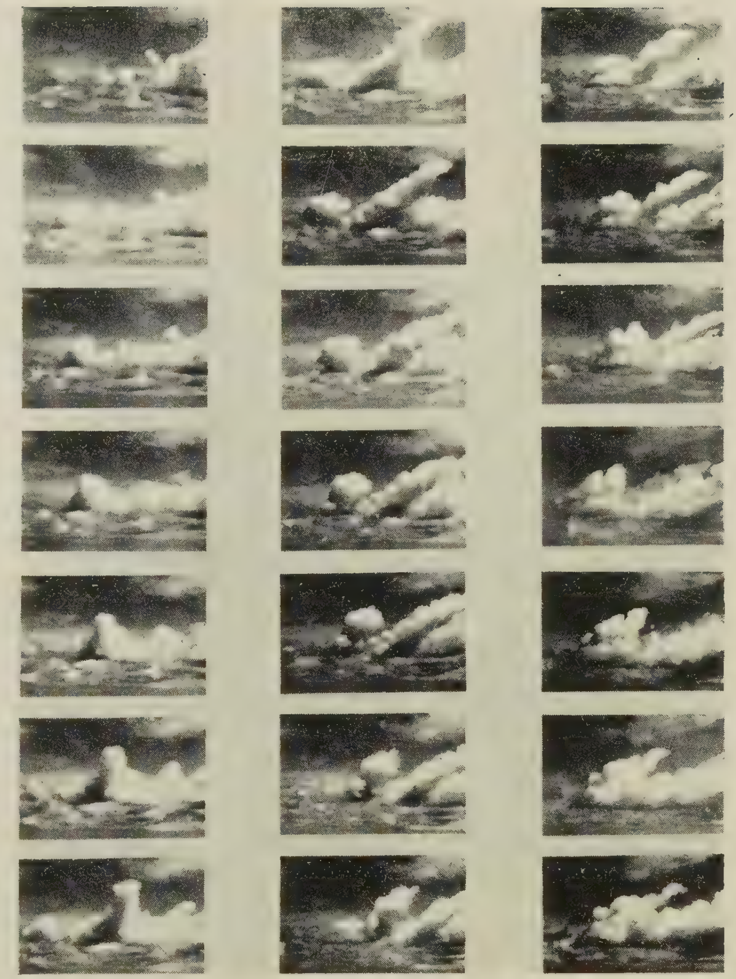

Figure 8. Sequence showing the life histories of several clouds over Nantucket Island on 8 Aug. 1950. Frames are reproduced every 30 sec beginning in the upper left. The horizon is not visible, but five radio towers were visible on the original prints, confirming reported locations and directions. The camera was pointed due east, at right angles to the surface wind which was from the north (left), increasing upwards. Cloud base was at 800 m, the highest tops reached about 1500 m.

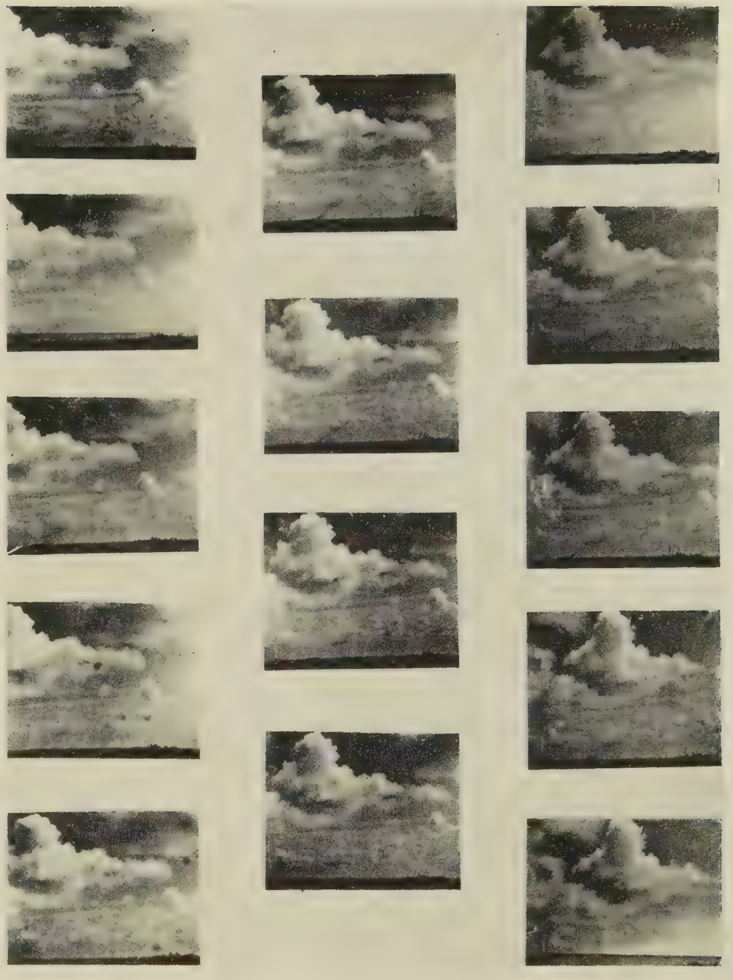

Figure 10. Sequence showing a cloud tower over Nantucket Island on 5 Sept. 1950. Frames are reproduced at 6-sec intervals. The camera is pointed east, at right angles to the surface wind which was from the north (left) and constant through the cloud layer. Note the vertical growth of the clouds.

operating against the growth of the clouds. It is interesting to check his theory by calculating the horizontal cloud speed from the theory presented here under the same assumption (namely that $Q = 0$, and so in Eqs. (14) and (15), $R = P$), then put this together with Stommel's calculated vertical motions to predict the cloud slope, which can finally be compared with Fig. 4. The other assumptions made by Stommel in arriving at the figures shown in Table I were identical with those used here in deriving Eq. (15), except that he assumed that the outside air mixed with the cloud air remained within the updraught, or that dM_0 was zero. His data permit the calculation of $P = \frac{1}{M}\frac{dM_i}{dz}$ for several height intervals without any assumption concerning how much of the entrained air was retained.

TABLE I.

z m above sea level	mass flux (in arbitrary units) if all air retained	vertical speed (m/sec)	$\frac{1}{M}\frac{dM_i}{dz} = P$ (calc.) $\times 10^5$	b (obs) $\times 10^3$	$(u_c - u_{E_0})$ m sec^{-1}
610	1·0	0			0
757	1·2	2·4	1·3	− 4·3	− ·06
915	1·7	3·6	2·8	− 4·3	− ·39
1070	2·1	2·9	1·6	− 4·3	− ·65
1220	3·2	0	3·5	0	− 1·18
			$P_{\text{ave}} = 2·3$		

Fig. 5 shows the calculated slope of the cloud. The slant is in the same direction (upwind) but somewhat less than that of most of the clouds photographed. The tilt of the actual clouds cannot have been exaggerated by more than 5 per cent by the altitude from which the picture was taken, since even those in the foreground were about 70,000 ft from the camera. In carrying through the individual steps of the calculation shown in the table, one finds that the only reasonable way in which the slope of the theoretical cloud could be significantly increased is by reduction of the vertical ascent speeds in its lower and central portions. It is not known in which, if any, of the depicted clouds the sounding used by Stommel was made and it may have been that most of those shown were in a later stage of their life cycles, or it may be that Stommel's method overestimates vertical velocities since it assumes that entrainment is the only resistance to the vertical growth of clouds. This question cannot be answered until photographs simultaneous with soundings are made of the same cloud. It should be noted that the wind shear on this day was considerably greater than normal for the trade-wind region, being 4·3 m sec^{-1} km^{-1}, a value more common in middle latitudes. The average value of P throughout the cloud layer came out to be $2·3 \times 10^{-5}$ cm^{-1}, noticeably greater than the average found by Stommel (1947) for trade cumulus (five cases, mean $P = 1·5 \times 10^{-5}$ cm^{-1}). In addition to stronger than normal decrease of easterlies in the cloud layer, the trade inversion was considerably lower than normal (base $\simeq$ 1200 m) and the cloud top had penetrated the drier, more stable air, as is seen from Stommel (1951) which shows negative buoyancy in the upper 330 m of the cloud. Except for these upper 330 m, the lapse rate through the cloud layer was 0·68°C per 100 m, and the mean mixing ratio 13·0 g/kg. Near the upper portions of the cloud, the lapse rate was 0·33°C per 100 m and the mixing ratio just under 5.0 g/kg. In this case, the cloud growth was clearly stopped by penetration of a stable dry layer, which served as a lid upon convection.

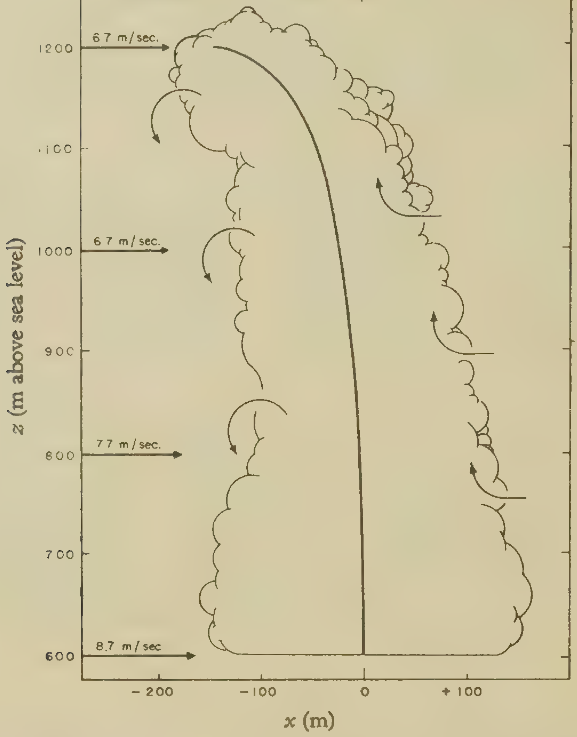

Figure 5. The theoretical slant of the trade cumulus of 25 Apr. 1946 studied by Stommel (1951) is given by the dark solid line. The dark arrows to the left are the observed external winds at San Juan at noon local time. The light curved arrows represent schematically the hypothesized air motions into and out of the cloud. The ' detrained ' air is shown descending outside the cloud in conformity with time-lapse motion pictures of cumulus.

(*b*) *Second case – an example of middle-latitude cumulus with strong negative shear.* Fig. 6 (Plate III) shows a series of time-lapse motion pictures made of a cloud formed over Nantucket Island, Massachusetts on 14 Aug. 1950. The photographs are reproduced at 30-second intervals. The camera was pointed in a direction normal to the surface wind, which was from nearly due south and decreased rapidly upwards. The average shear through the cloud layer was 5 m $\sec^{-1}$ km^{-1}. Aeroplane records (see Malkus and Bunker 1952) gave the height of the cloud bases (450 m) and their location with respect to the camera. This knowledge permitted the rate of rise of the cloud tower to be calculated from the film and hence an estimate of the ascent rates within the cloud. The tower reached its greatest height in the 23rd frame or 11½ minutes after it began to grow, giving a mean rate of rise of about 2 m $\sec^{-1}$. Between the 19th and 21st frames the tower ascended at an average rate of slightly more than 3·0 m $\sec^{-1}$.

The observed slope at one-minute intervals beginning with the 20th frame has been plotted in Fig. 7. Assuming a mean vertical draught speed of 3 m $\sec^{-1}$ prevailed at this time, the slope could be exactly duplicated from the theoretical model if a total frictional coefficient of $R = 2{\cdot}5 \times 10^{-5}\ \mathrm{c/m}^{-1}$ were taken as the mean value for the entire cloud and if it were assumed that the updraught began at 150 m below the cloud bottoms and increased linearly up to 3 m $\sec^{-1}$ at cloud base. From the observed vertical speed in the 20th frame (w_0 in Fig. 7), vertical speeds for the 22nd, 24th, 26th,

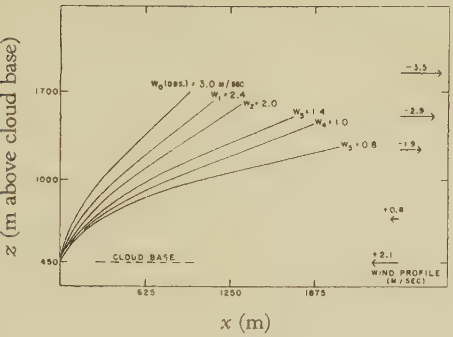

Figure 7. Observed slant of cloud (14 Aug. 1950) depicted in Fig. 6 at one-minute intervals beginning with frame 20. The vertical speed w was observed from the film; those remaining (w_1, w_2, etc.) were calculated from the slopes. The pilot-balloon observation made within a few kilometres of the clouds is reproduced on the right.

28th, and 30th frames (w_1, w_2, w_3, w_4, and w_5, respectively) could be calculated from the observed slopes shown in the figure, using the same value of R. The decay of the draught, and all the other computed values seem to present a reasonable and consistent picture. Concerning the relative contribution to R by form drag and entrainment, it is important to note that the upper limit of Q in this case is probably about $0{\cdot}4 \times 10^{-5}\ \text{cm}^{-1}$. This coefficient was computed from Eq. (11) using $C_D = 1{\cdot}5$, together with the observed cloud diameter, calculated relative speeds and vertical motions. This sets a lower limit for P, the fractional rate of entrainment, as $2{\cdot}1 \times 10^{-5}\ \text{cm}^{-1}$, a value of the same order of magnitude but about 40 per cent larger than the mean rate inferred by Stommel. In the present example, the horizontal motion of the cloud was so small, as was the wind speed, that an accurate calculation of the relative cloud-air speed from the film was not feasible.

It is interesting to note that this cloud was able to put up only one tall tower, reaching barely over 2 km, although abortive attempts to raise at least two others from its left side are obvious from the photographs. The cutting off of the one tall tower in the region of strongest shear (1,000 m to 1,500 m) is also noteworthy. Throughout the entire cloud layer and far above its top, the lapse rate maintained a nearly constant value of 0·69°C/100 m, so that it is not possible to ascribe either the limitation of the cloud's growth or the cutting off of the tower to any stabilization of the air. It is concluded that this cloud was curtailed and eventually killed by entrainment of drier air, especially since the parcel method shows vast amounts of energy available for its growth up to at least 4 km (the radiosonde and other details of this case are discussed by Malkus and Bunker 1952). The observed moisture distribution supports this conclusion. In the subcloud layer the mixing ratio averaged nearly 10 g/kg; from cloud base to 1 km, it averaged 7·1 g/kg, from 1 km to cloud top at 2 km its mean value was 5·4 g/kg and from 2 km to 4 km, 3·8 g/kg. It is inferred that strong wind shear gave rise to both a high entrainment rate and a strongly slanting cloud, which factors coupled with a very dry environment served to inhibit the cloud's growth.

(*c*) *Third case – an example of middle-latitude cumulus with weak positive shear.* Fig. 8 (Plate IV) shows another series of time-lapse motion pictures made over Nantucket Island on 8 Aug. 1950, and again reproduced at 30-second intervals. In this case, the wind remained from due north at all levels (from left to right across the plane of the photographs) and increased upward. The shear was $+3{\cdot}0\ \text{m sec}^{-1}\ \text{km}^{-1}$ from 600 m to

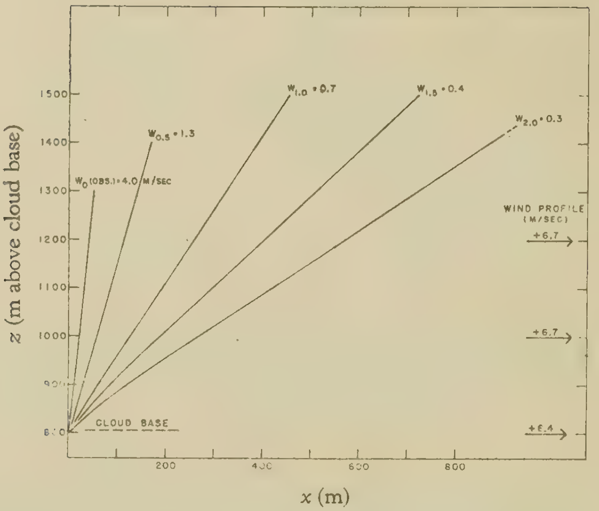

Figure 9. Observed slant of cloud (8 Aug. 1950) depicted growing in frames 1-7 of Fig. 8 at half-minute intervals. The vertical speed at the 6th frame, w_0, was observed from the film, those remaining were calculated from the slopes. The pilot-balloon observation made within a few kilometres of the clouds is reproduced on the right.

900 m, and nearly zero from there up to 1,200 m. Cloud base was observed from the plane to be at 800 m, and the cloud location was also specified in this manner. The calculations were made for the first cloud tower in the series, which commenced to grow actively in the 2nd frame, reached its maximum elevation in the 10th (after 4 min) and 3 min later had all but disappeared. The average rate of rise of this tower was 4 m $\sec^{-1}$, and this differed little from one frame to the next. The maximum rate of rise occurred between the 5th and 6th frames. The observed slopes for the 6th to the 10th frames are plotted in Fig. 9.

The curve for the 6th frame was exactly duplicated from the theoretical model under two assumptions : first, that the average total friction coefficient R was equal to $2{\cdot}0 \times 10^{-5}$ cm^{-1}; and second, that the updraught began at 300 m below cloud base, increasing linearly up to 4 m $\sec^{-1}$ at 100 m above cloud base. From these same assumptions, the observed slopes at half-minute intervals for the 7th to the 10th frames were found to correspond to the rate of updraught decay shown in Fig. 9. Note the very much more rapid decay than in the preceding case. Owing to the greater windspeed on this day, it was possible to calculate fairly accurately the relative horizontal cloud-air speed from the films. These calculations showed that the central portions (at about 1 km elevation) of the clouds were moving downwind at approximately 1·2 m $\sec^{-1}$ slower than the external wind. The relative velocity obtained from theoretical considerations was 1·3 m $\sec^{-1}$ at 1,100 m, in excellent agreement.

The lapse rate from 800 m to 1,500 m (cloud layer) on 8 August was given by the Nantucket radiosonde as about 0·5°C/100 m, steepening slightly above this. No very stable layers or inversions were observed. The mixing ratio averaged 7·1 g/kg in the cloud layer and had fallen to 5·5 g/kg at 2 km. Computations by means of the parcel method showed only a rather small positive area within the cloud layer, with the moist adiabat recrossing the sounding at about the height of the observed cloud tops. Therefore the lack of continued cloud growth is readily understandable.

Eq. (11) shows that the maximum value of Q would be about $0{\cdot}8 \times 10^{-5}\,\mathrm{cm}^{-1}$, using $C_D = 1{\cdot}5$. This means that the minimum value of the fractional entrainment rate, P, is $1{\cdot}2 \times 10^{-5}\,\mathrm{cm}^{-1}$.

(*d*) *Fourth case – an example of middle-latitude cumulus with negligible shear.* Fig. 10 (Plate IV) shows a series of Nantucket clouds photographed around noon on 5 Sept. 1950. These are reproduced at 6-second intervals. The cloud base averaged 600 m and at this time of day most of the tops terminated at about 900 m. From 300 m to 1 km the wind was constant in both speed and direction, $8{\cdot}9\,\mathrm{m\,sec}^{-1}$ from 360°, or from left to right across the photographs. From 1 km upward it decreased, becoming $6{\cdot}7\,\mathrm{m\,sec}^{-1}$ at 1,965 m.

Since the clouds in the photographs were developing vertically, as predicted, the frictional forces could not be computed. The mean ascent rate of the cloud tower shown was slightly greater than $1\,\mathrm{m\,sec}^{-1}$ during this short period. The slow rise of the turret was probably due to the fact that it had already penetrated the small inversion at 900 m, to be discussed presently. The horizontal speed of this cloud came out, within computational error, to be exactly that of the wind.

The aeroplane sounding over the island (see Malkus and Bunker 1952) made just before noon showed a lapse rate of 0·59°C/100 m from cloud base up to about 900 m, at which level a small inversion occurred. The average mixing ratio for 600 m to 900 m was 7·8 g/kg. The parcel method showed positive energy from cloud base up to the small inversion and, if that rather small negative area were surpassed, more positive energy up to a very strong inversion at 2·1 km. The temperatures inside these clouds were higher than outside near their bases and lower than outside near the tops where they had penetrated the small inversion.

Succeeding series of time-lapse pictures (not reproduced owing to poor photography) continuing into the afternoon showed an interesting sequence of cloud development. At first the cloud tops were cut off in the small inversion and dissipated directly above their lower portions. Later, successive towers of the same cloud penetrated higher and higher, until it was clear that they had destroyed the small inversion. Around 1425 EST the aeroplane observer noted towers reaching 1,500 m to 1,600 m, and slanting strongly backward as they penetrated the region of negative wind shear. Observations made within these clouds showed their tops to be warmer than the environment air. No towers were noted which reached the base of the large inversion at 2·1 km. This case was considered to be a particularly valuable one, as it showed clouds first being stopped by, then destroying, a small stable layer, then being inhibited by friction and entrainment of drier air aloft.

4. Conclusion

It has been shown by means of the very simple and unequivocal measurement of cloud slope that entrainment or mixing occurs in several examples of cumulus clouds to the same magnitude inferred by Stommel (1947) from aeroplane-psychrograph soundings. It can hardly be doubted any longer that interaction of a significant degree takes place between cumulus clouds and their surroundings and plays an important, frequently vital, role in the dynamics of the clouds, at least in their small and swelling cumulus stages. The balance achieved between vertical motions and mixing controls the release of latent heat by condensation (which in turn exerts a reverse control on vertical draughts and mixing) and hence even the microphysics of clouds, drop-growth rates and size distributions, may be expected to be markedly influenced by such macroscopic external variables as wind shear.

This paper does not purport to answer the very serious questions concerning the mechanisms of ' entrainment,' whether it consists mainly of an ordered inflow, or of a turbulent mixing process resembling that in a heated jet, nor does it tell much concerning the functional dependence of entrainment rates upon the other variables. Further observations of the type suggested here, including those of cloud slopes, however, may be expected to provide this information. In concluding, it must be emphasized that a cloud is a process, not an entity like a pilot balloon. What we call a single cloud may completely exchange its air several times during its life cycle. Future observational work must, therefore, be planned to obtain a wide variety of measurements within the cloud and to relate them to the structure of its environment. To this end, high refinement in individual observations is at the present stage probably worth sacrificing.

ACKNOWLEDGMENTS

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She would also like to acknowledge the contribution made by Dr. Patricia A. Langwell, in collaboration with whom her work on cloud slopes was initiated.

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Contribution No. 610

BREVIORA

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A NEW SPECIES OF THE CYCLOSTOME GENUS *PARAMYXINE* FROM THE GULF OF MEXICO

By Henry B. Bigelow and William C. Schroeder[1]

Up to the present time the myxinids, represented in the North Atlantic by the unibranchiate genus *Myxine* alone, have been unknown in the Gulf of Mexico. During 1951, however, the experimental trawlings of the U. S. Fish and Wildlife Service vessel "Oregon", in the northern part of the Gulf, yielded three specimens of a myxinid with six pairs of external gill openings that agree closely with the genus *Paramyxine* Dean 1904, reported previously from Japan only.[2] *Paramyxine*, originally described from a single specimen, as the new species *P. atami* Dean 1904, is characterized, by its author, by having the outer "branchial ducts of distinctly unequal length, the most anterior several times the length of the posterior" (Dean, p. 22), so that the most anterior pair of external gill openings is opposite the 4th or 5th pair of internal gill sacs; and by having the successive pairs of gill openings close together. In other known myxinids with more than one pair of gill openings the successive pairs of external branchial ducts are of approximately equal lengths, or the 1st pair is only a little longer than the rearmost pair, and the successive pairs of gill openings are more widely spaced. On the type specimen the gill openings themselves were oval, with their long axes transverse (except for the 6th opening on the left-hand side, which — receiving the oesophageal duct — is larger than the others), not round as they are in other polybranchiate species. But the gill openings were of various shapes in other specimens described subsequently by Matsubara (1937), showing that their shape is not a generic character as Dean supposed,

[1] Contribution No. 610, from the Woods Hole Oceanographic Institution.

[2] We owe to Mr. Stewart Springer the opportunity of studying these interesting specimens.

or even a specific character, but is, likely, dependent to a considerable extent on the degree of muscular contraction. This leaves only the relative lengths of the external branchial ducts and perhaps the close spacing of the gill openings, as compared with other myxinids in which they are few in number, as bases for separating the genus *Paramyxine* from other polybranchiate myxinids. We accept the genus provisionally, awaiting the opportunity of examining other myxinids with corresponding numbers of gill openings.

Characters that Dean (1904, p. 22) included as specific for *P. atami* were the precise number (6) of pairs of gill openings; 1st pair of external branchial ducts about 3 times as long as the 6th pair; 12 and 13 lingual teeth in the outer rows with 13 in each of the inner rows; anterior 3 lingual teeth of each row fused with one another at their base; white gill openings and conspicuously dark mucous pores. His illustration also shows a rather pointed snout, resembling that of *Myxine*, but a somewhat broader and more paddle-shaped caudal fin fold.

The gill openings of the type specimen of *atami* occupied a space about 9 per cent as long as the distance from the tip of the snout to the most posterior pair of gill openings,[1] with those on each side arranged close together in a regular row, and they are arranged similarly in an excellent specimen of *atami*, from Suruga Gulf, Japan, received recently by the U. S. National Museum (U. S. Nat. Mus. No. 161442). But Matsubara's (1937) observations have shown that the serial arrangement of the gill openings, like their shapes, may vary widely from individual to individual, and even between the two sides of the body of a given specimen, for they were irregularly arranged in 13 of his 14 specimens. Muscular contraction may play a role here. Matsubara also found that the dental formula is not a precise one, for his specimens had only 10 or 11 lingual teeth in each row, outer and inner, with only the first two fused at the base instead of three as was true of the type specimen.

The Gulf of Mexico specimens agree in general with the accounts and illustrations of the Japanese *atami* and with the National Museum specimen, in body form, with rather pointed snout and a caudal fin fold somewhat wider than that of *Myxine*. Their barbels are similar to those of *atami* in length and in arrangement; they have the same number (6 pairs) of external gill openings; the external branchial ducts (as measured by probing) are about as long relative to the 6th pair;

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[1] As scaled from Dean's (1904, pl. 1, fig. 3) illustration.

the foremost pair is situated about as far rearward while the gill openings cover about as long a space relatively; the distribution of mucous pores is about the same; also the linear dimensions in general, as appears from the following tabulations:

Table 1

Distances, in Per Cent of Total Length

	Gulf of Mexico specimens, 338, 055 and 590 mm.	*atami*, Japan type 550 mm.	*atami*, U. S. Nat. Mus. specimen 500 mm.
Snout to foremost mucous pore	7.5– 8.7	6.8	9.0
Snout to foremost gill openings	22.5–23.5	26.0	27.0
1st gill opening to 6th gill opening..................	2.4– 5.7	2.5	2.4
6th gill opening to tip of caudal fin fold..................	72.0–74.3	71.4	73.0
Snout to origin of anal fin fold	37.1–50.0	41.4	43.4
Cloacal pocket (center) to tip of caudal fin fold..........	13.4–17.5	12.8	13.2

Table 2

Numbers of Mucous Pores on Each Side

	Gulf of Mexico specimens	*atami*, type[1]	*atami*, U. S. Nat. Mus. specimen
Snout to foremost pair of gill openings.................	15-15 to 19-19	19–20	16–16
6th pair of gill openings to cloacal pocket............	44-45 to 57-57	58–59	47–47
Center of cloacal pocket to tip of caudal fin fold..........	11-11 to 13-14	?	10–10

The number of lingual teeth, too, is about the same in a Gulf of Mexico specimen of 505 mm. (14 and 13 in the outer rows, 11 and 12 in the inner rows) as it was in the type specimen of *atami*, with the same number (3) of anterior teeth fused basally in each of the outer two rows. And while two only, of the anterior teeth in each of the inner rows are fused in the Gulf of Mexico specimen, three were fused in the type, and Matsubara (1937, p. 15, text fig. 3) has already reported and figured Japanese specimens that agreed with the Gulf of

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[1] From Dean 1904, p. 11, text fig. 2, D.

Mexico one in this respect. The series of mucous pores on each side is interrupted near the anterior end of the cloacal pocket on the U. S. National Museum specimen of *atami* (Fig. 6), just as it is in the Gulf of Mexico specimens (Fig. 5) — in *Myxine* too, for that matter — to continue rearward at a higher level. Representation of it in Dean's (1904,pl. 1, fig. 3) illustration as continuing unbroken past the cloacal pocket seems to have been an error by the artist. But the rearward pores are situated higher above the ventral edge of the caudal fin fold in the Japanese *atami* (Fig. 6) than in the Gulf of Mexico specimens (Fig. 5).

The depth, too, of the body relative to the distance from tip of snout to 1st pair of external gill openings is greater on all three of the Gulf of Mexico specimens (34 per cent to 37 per cent) than is pictured for *atami* either by Dean (30 per cent) or by Matsubara (22 per cent), or than it is on the U. S. National Museum specimen of *atami* (29 per cent). And while the hagfishes are so soft of body that measurements of different specimens cannot be accepted as precisely comparative unless taken under equal tension, the difference in this respect between the two geographic populations may be large enough to be significant. The shape of the caudal fin fold also differs rather noticeably, its lower margin being nearly straight in all three of the Gulf of Mexico specimens while it is pictured as moderately convex in the two Japanese specimens of *atami* which have been illustrated (Dean 1904, pl. 1, fig. 3; Matsubara 1937, pl. 1, fig. A), likewise in the National Museum specimen of *atami* (compare Fig. 5 with Fig. 6).

Furthermore, neither of the two larger Gulf of Mexico specimens shows any trace of a dorsal fin fold anterior to the level of the cloacal pocket, whereas Matsubara's (1937, pl. 1, fig. A) illustration of *atami* clearly shows such a fold, extending forward for one third to one half the distance from the level of the cloacal pocket toward the level of the 6th pair of gill openings while the dorsal fin fold on the National Museum specimen of *atami* is continued forward as a definite though low dermal ridge to abreast of the 6th pair of gill openings.[1]

These differences between the Gulf of Mexican and the Japanese representatives of the genus seem sufficient, in combination, for recognition in nomenclature. We therefore propose for the former the new specific name *springeri*, as defined below. What is most interesting, however, in this case, is not that the Gulf of Mexican population differs in minor ways from the Japanese — it would be astonishing if such were not the case — but that two populations so widely separated should resemble each other so very closely, and that myxinids with five to seven pairs of external gill openings should have been found at localities as widely separated as the Gulf of Mexico, Japan and China, New Zealand and South Africa, but nowhere else in the oceans.[1] This instance does not stand alone as it concerns the Gulf, for the chimaeroid *Hydrolagus alberti* Bigelow and Schroeder 1951*a*, recently discovered in deep water there, seems more closely allied to the Japanese *H. mitsukurii* (Dean) 1904, than it is to either of the two species of its genus that are known from the North Atlantic, i.e., *affinis* (Brito Capello) 1868, and *mirabilis* (Collett) 1904, or than it is to *H. collei* (Lay and Bennett) 1839, of the Pacific coast of North America. Equally unexpected was the recent discovery, in the Gulf, in moderately deep water, of a representative (*Springeria folirostris* Bigelow and Schroeder 1951), of the rajoid family Anacanthobatidae, for the latter had been known before only off the Natal coast of southeast Africa; also of two representatives of the skate genus *Cruriraja* in Cuban-Floridan waters (*C. atlantis* and *C. poeyi* Bigelow and Schroeder 1948), for this genus, too, had been known only off Natal, southeast Africa, previously.

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[1] The anal fin fold also, of the National Museum specimen of *atami* is continued forward nearly to the 6th gill opening as a prominent dermal ridge. But the appearance of the latter, in alcohol, suggests that it was the result of aulmuscr contraction, not a normal characteristic.

Altogether, the bottom zone in the Gulf and around Cuba at 75 to 600 fathoms has yielded three new species of sharks, eleven new batoids, and one new chimaeroid since 1938, a foretaste of the rich harvest of unknown fishes to be expected from a more thorough exploration of the deep slopes and of the sea floors of the Gulf and of the Caribbean.

PARAMYXINE SPRINGERI, new species[2]

Type. A specimen, 590 mm. long, Oregon Station No. 489, Lat. 27°44′N., Long. 85°09′W., 254 fathoms, Sept. 29, 1951 (U. S. Nat. Mus. No. 161512).

Additional material. Another specimen 505 mm. long from the same trawl haul, and a third, 338 mm. long, from Oregon Station No. 321, Lat. 27°27′N., Long. 87°19′W., 220 fathoms, April 28, 1951. The sex has not been determined for any of these specimens.

Description. Dimensions, in per cent of total length, of type (590 mm.), 505 mm. specimen, and 338 mm. specimen.

Depth of body, at 1st gill openings, 9, 7.8, 8.9.

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[1] For a synopsis of the species of myxinids, see Holly, 1933.

[2] Named after Stewart Springer who discovered this interesting cyclostome.

Distance, snout to 1st gill openings, 23.5, 23.2, 22.5.

Distance, 1st gill openings to 6th gill openings, 2.4, 2.6, 5.7.

Distance, snout to origin of anal fin fold, 50.0, 37.1, 39.8.

Distance, center of cloacal pocket to tip of tail, 14.5, 13.4, 17.5.

Depth, in per cent of distance, snout to 1st gill openings, 38, 34, 37.

Number of mucous pores on each side, type (590 mm.), 505 mm. specimen and 338 mm. specimen:

Snout to 1st gill openings, 19-19, 18-18, 15-15.

1st gill openings to 6th gill openings, 4-3, 3-3, 6-6.

6th gill openings to anterior end of cloacal pocket, 55-56, 57-57, 44-45.

Anterior end of cloacal pocket to tip of caudal fin fold, 13-14, 11-11, 12-12.

Snout obtuse-conical, much as in *Myxine*; body cylindrical anteriorly, about 80 to 100 per cent as thick (transversely) at region of gill openings as deep there, but increasingly compressed posteriorly, until only about 38 to 54 per cent as thick as deep at level of cloacal pocket, and flat sided thence rearward to paper-thin margin of caudal fin fold. Depth of body about 5.4 to 6 per cent as great as total length at level of most anterior mucous pores, about 6.3 per cent at anterior end of cloacal pocket on type, and 6.6 to 8.6 per cent on smaller specimens.

Fleshy rostrum, anterior to nasal opening, broadly rounded anteriorly and wider than long,[1] the nasal opening conspicuous below it. Barbels in the typical myxinid arrangement, the 1st pair about two-thirds as long as the 2nd pair, the 3rd pair a little the longest. Mouth, when closed, with the usual puckered or irregularly stellate appearance, the conical projection that flanks it on either side about as long as the 2nd pair of barbels. Thirteen and fourteen lingual teeth in the outer rows, eleven and twelve in the inner rows of 505 mm. specimen[2], individual teeth conical with slightly blunted tips, curving a little rearward, the most posterior of each inner row strongly so; the 5th and 6th tooth longest in each row; the 7th and the following teeth successively shorter along each row; the rearmost only about one-third as long as the 5th and 6th. The first three teeth in each outer row, and the first two in each inner row fused at their bases; the outer row in each side about 1.2 times as long as the inner row; the longest teeth in the outer rows about 1.3 times as long as the longest in the inner rows.

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[1] Longer than wide in *Myxine*.

[2] The teeth of the type specimen cannot be counted without dissection.

The six pairs of gill openings are low down on the sides, their fore-aft position as given in Table 1 (p. 3), occupying a shorter space on larger specimens (2.4 per cent of total length on the type) than on smaller, the series on the two sides converging rearward, with the 6th pair only about three-fourths as far apart as the 1st pair on the type, about four-fifths as far apart on the smallest specimen; the 6th opening on the left-hand side (receiving the oesophageal duct) larger than the others as is the rule among myxinids, and irregular in shape, the other gill openings ranging in shape from round to oval with the long axis transverse or slightly oblique, the precise shape seemingly dependent on muscular contraction; the largest (apart from the 6th left-hand) a little less than one-half as long as the 3rd (longest) pair of barbels. The gill openings are either in regular serial arrangement on each side as on the type (Fig. 2) and on the smallest specimen, or more or less irregular at least on one side, as on the 505 mm. specimen (Fig. 3), a difference perhaps associated with muscular contraction. The 1st pair of external branchial ducts (as sounded by probing, on one side of the body) are about three times as long as the 6th pair, both on the type and on the 505 mm. specimen.

The mucous pores range in size from easily visible to so minute as to be discernible only on close examination. Their location on the body and in serial arrangement is as in the other myxinids; 19 pores on each side from snout to 1st gill openings on the type, 4 on one side and 3 on the other abreast the gill openings, 55 and 56 between gill openings and cloacal pocket and 13 and 14 rearward from the anterior end of the cloacal pocket on the type specimen; their numbers on the other specimens as given in Table 2 (p. 3). Totals of 77 pores on the 338 mm. specimen, of 88 on the 505 mm. specimen, and 92 on the 590 mm. specimen (type) show that the pores increase in number with growth. The pores along the section occupied by the gill openings are ventral from the latter, which it seems is characteristic of the polybranchiate myxinids in general.

The pores rearward from the gill openings are nearly in line with the latter, are low down on the sides nearly to the anterior end of the slit-like cloacal pocket, where the series is interrupted, with the nine posterior pores situated at a definitely higher level, a distinctive character of this species as contrasted with the Japanese *atami* (p. 4). On the type, those rearward from the cloacal pocket are also noticeably larger (hence more conspicuous) than those farther forward, and they are somewhat more conspicuous than the more anterior pores on the

505 mm. specimen as well. But this regional difference in size of mucous pores is not a specific character; rather it is likely a phase of muscular contraction, for the pores of the caudal series on the smallest specimen are no larger than those anterior to the cloacal pocket.

The point of origin of the anal fin fold, about midway of the body on the type specimen, is considerably farther forward on the other two specimens (see Table 1, p. 3) showing that its precise situation is variable within rather wide limits. On the type, the fold itself is so narrow that its width is hardly measurable, and it is traceable rearward only about half the way from its point of origin toward the cloacal pocket. But it is wider on the other specimens (8 to 13 per cent as wide as the body is deep), and traceable rearward nearly or quite to the cloaca. To what degree these differences are associated with different stages in growth, or in the sexual cycle, is a question for the future.

Neither the type, nor the 505 mm. specimen shows any trace of a dorsal fin fold anterior to the level of the cloacal pocket, their backs being evenly rounded, in which respect they contrast with *P. atami* as pictured by Matsubara (1937, pl. 1, fig. A). And while the smallest (338 mm.) specimen has a low fleshy ridge all along the back nearly to the level of the mouth, the fact that it is flanked on either side by a shallow and indefinite furrow suggests that it is the result of muscular contraction, rather than a definite and persisting fin fold. The caudal fin fold fringes the rear section of the trunk, from about opposite the anterior end of the cloacal pocket on the dorsal side, around to the posterior end of the cloaca on the ventral side. Its lower outline is nearly straight as remarked above (p. 4). The irregular fluting of its broadly rounded, posterior-dorsal margin on the smallest specimen (Fig. 5) seems to represent its normal outline better than its margin on the type, (Fig. 1) where it seems to have been injured.

One of the most interesting features of *P. springeri*, reported to us by its discoverer, is that no one of the specimens discharged any mucus at all when brought on board, or so little that none was noticed.

Color. All three specimens are greyish brown, faintly tinged with reddish, below as well as above, the edges of the caudal fin fold and of the anal fin paler; the gill openings encircled with white, rendering them conspicuous against the dark background; the mucous pores appearing as dark brown dots, each of them at the bottom of a shallow depression of the skin.

Size. The maximum size is not known.

Range and habits. So far known only from the northern side of the Gulf of Mexico, at the localities listed on page 5. The depths of capture, added to the fact that fishermen have never reported it, show that it is a deep-water species. Nothing else is known of its habits.

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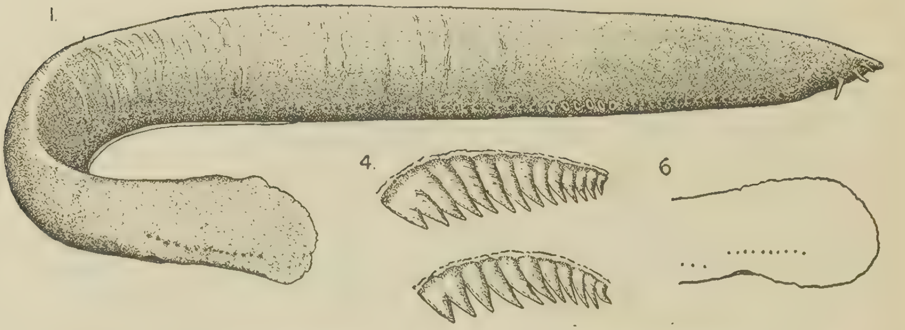

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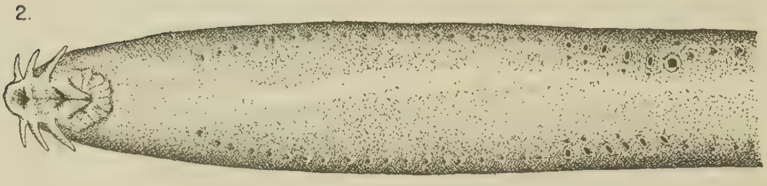

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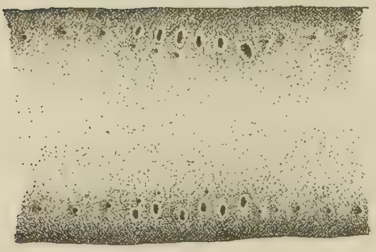

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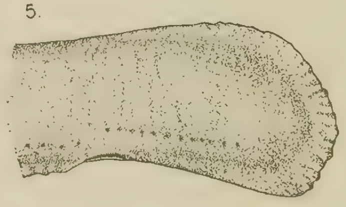

Fig. 1. Type specimen, x ¼; the mucous pores somewhat exaggerated.

Fig. 2. Ventral view of anterior part of type specimen, x ½; the mucous pores somewhat exaggerated.

Fig. 3. Ventral view of gill region of specimen 505 mm. long; natural size; the mucous pores somewhat exaggerated.

Fig. 4. Lingual teeth of specimen 505 mm. long, from the right-hand side; outer row above, inner row below, anterior ends to the left, x 2.

Fig. 5. Side view of caudal region of specimen 338 mm. long, x ½; the mucous pores slightly emphasized.

Fig. 6. Side view of caudal region of *P. atami*, 500 mm. long, from Suruga Gulf, Japan, U.S. Nat. Mus.,No. 161442;the mucous pores slightly emphasized.

Contribution No. 611

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Sport Fishes of the Vicinity of the Gulf of Honduras, Certain Caribbean Islands, and Carmen, Mexico*

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GULF OF HONDURAS AND THE CARIBBEAN

PART I

A study of the fishes in the vicinity of the Gulf of Honduras was made in conjunction with an archeological survey of the region. The expedition was made in January and February, 1950, under the auspices of the Institution for Andean Research, Inc. The sport fishing possibilities of the area were explored, as there appears to be no published information on this subject. The survey was not made in the best fishing season and the party moved on so frequently that no one locality could be thoroughly investigated, but it is hoped that the information contained herein may be of some assistance to persons who have occasion to be in the areas studied and wish to try the sport fishing. This paper groups the facts discovered with the species of fish concerned, while a regional summary at the end of each part lists the species seen and also enumerates fish which were not seen but whose presence was reported by local people. While only the sport fish are discussed here, a collection including other local fishes was made for later study.

Mr. Charles S. Bird, Colonel John K. Howard and the archeologists Dr. Alfred V. Kidder, Dr. Gordon Eckholm and Mr. Gustav Stromsvik, as well as Captain Matthew English of the vessel "Irmay" and his crew, all contributed greatly to the success of the ichthyological work. Valuable assistance was also obtained from officials of the United Fruit Company and from Mr. R. K. Masson, Port Captain and Collector of Customs at Belize. Dr. Lionel A. Walford, Chief of the Branch of Fishery Biology, U. S. Fish and Wildlife Service, directed the first ten days of intensive collecting, setting up procedures which were followed during the remainder of the trip.

There are scattered populations of tarpon (*Tarpon atlanticus*) in rivers and lagoons of the northwestern Caribbean. The Trujillo area was the only one on the coast of Honduras in which these fish were encountered. In the canal at Puerto Castilla, many strikes were obtained by trolling small spoons and two or three very small tarpon were landed. The fish striking appeared to range from three to twelve pounds, except for one which looked to be of nearly fifty pounds. Residents said that tarpon had frequented the steamer dock at Puerto Castilla when it was used by the fruit ships. Some of these fish were also seen in the entrance to the lagoon of Guaimoreto, where fishermen reported that they often caught them. Tarpon were said to be plentiful in various lagoons on Utila Island and there are probably other places on the coast of Honduras and among the Bay Islands where they occur.

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* Contribution No. 611 from the Woods Hole Oceanographic Institution.

The coast of Guatemala appears to offer greater possibilities for the tarpon fisherman than that of Honduras. Many tarpon were seen in the Rio Dulce between Livingston and the Golfete, but only three strikes were obtained. This river undoubtedly supports a large population of tarpon and it can be fished a great distance further inland. First hand information indicated that there is often excellent tarpon fishing in the Graciosa River or Hospital Bight, although no fish were seen on the single visit made there.

In British Honduras there are several places which offer good tarpon fishing. A "tarpon hole" near Frenchman's Cay was found with the assistance of native fishermen. Tarpon which were rolling in schools ignored trolled lures but struck at fresh water bass plugs of the swimming type when these were cast accurately among them. One fish of about forty pounds was hooked but parted the light line after running clear across the pool into the mangroves.

In the Manatee River there were times when small tarpon would hit the plug on almost every cast, if a snook or jack crevalle did not get it first. On these occasions, the fish were showing among the mangrove roots on the banks. Some large tarpon were raised by casting, but they more frequently struck lures trolled in mid-stream. The larger fish appeared to be more solitary in their habits than the smaller ones. The tarpon landed here weighed from four to eight pounds, but some of those lost appeared to weigh well over fifty pounds.

The Belize and Sibun Rivers were also said to afford good tarpon fishing. The lighthouse keeper at Cay Bokel directed the party to some creeks among the Turneffe Islands which he said were good tarpon waters, but only one strike was obtained in the short time fished.

At Grand Cayman, two of the party fished for tarpon in small, landlocked lagoons. Natives said that the fish came from the sea through subterranean passages. Many little tarpon were seen rising but they struck only half-heartedly on small plugs. A member of the party who remained on the island caught one by using a live minnow for bait. Natives reported that larger tarpon are caught in the shore waters.

Ten-pounders (*Elops saurus*) were reported to inhabit the entrance to the lagoon of Guaimoreto near Trujillo. Three were taken by plug casting in a school which surfaced at night around the boats in Belize Harbor, while others were caught or hooked on plugs and feather lures in the Manatee River. These fish take swimming plugs. Those caught weighed about four pounds each.

The bonefish (*Albula vulpes*) inhabit many of the flats of the northwestern Caribbean. Some were caught in the beach net at Cape Honduras off Trujillo, and one was seen at Tela. Many schools of these fish were seen on a flat near the harbor entrance at Utila Island and natives reported that they were far more numerous in a cove on the north side. Others were observed on flats near Coxen Hole, on Roatan Island, and they were said to be plentiful on Bonacca Island. Soldier crabs (*Pagurus*) were the preferred bait for bonefish among the Bay Islands.

The waters of British Honduras evidently support a considerable population of bonefish. Several very small ones were seen in the live well of a fishing boat at Frenchman's Cay. Larger specimens, weighing from about three to six pounds, were for sale in the markets at Stann Creek and Belize. A few schools were seen on the flats near Cay Bokel Light. The keeper reported that bonefish had been very plentiful, but that the local population was now reduced in numbers by seining. He recommended conch for bait and chum. No strikes were secured in the very short time spent fishing there but it is probable that the bonefish enthusiast could find plenty of these fish in this region.

The great barracuda (*Sphyraena barracuda*) was one of the most common reef fish in the northwestern Caribbean. In the Trujillo area the party did not fish the reefs, but took some of these fish in the entrance to the lagoon of Guaimoreto and in Trujillo Bay where they were said to frequent the steamer dock at Puerto Castilla. They were not caught at the other places fished along the coast of Honduras, most of which were sandy.

Among the Bay Islands barracuda were caught in greater numbers than any other species, taking almost any lure trolled near the reefs. These fish ranged from four to twelve pounds in weight. Some small ones were also taken in the vicinity of Puerto Barrios in Guatemala.

In British Honduras, numerous barracudas were caught along the barrier reef, off Cay Bokel and at Glover Reef, the largest weighing twenty-one pounds. Inside the barrier they were not so plentiful, but a few were taken in river mouths and around the inner reefs and cays. Several barracuda were boated in the short time spent fishing at the Swan Islands.

The barracuda took practically every type of lure voraciously, but a large spoon trolled on a wire line seemed the most attractive in the deeper waters.

Blackfin tuna (*Parathunnus atlanticus*) and false albacore (*Euthynnus alletteratus*) were found in the vicinity of the Gulf of Honduras.

Blackfin tuna of about 3 pounds were taken between Trujillo and Bonacca Island, and small schools of these fish were seen near the Hog Islands, while other schools which may have been of this species were observed near Tela and Puerto Cortes.

Larger schools of small blackfin tuna were found among the Bay Islands, but rod and reel fishing was made almost impossible by the sharks which shadowed the tuna and seized them as soon as the latter started struggling on the line. The blackfins often were shy and refused to strike, but on one occasion ten were taken on handlines in a half-hour with small feather lures and 6/0 hooks. A few solitary blackfin tuna and false albacore were caught by trolling along the reefs or banks. These fish ranged from about two to seven pounds in weight.

Off British Honduras, schooling blackfins were seen inshore of Glover Reef and the Turneffe Islands but none were caught. Some small false albacore were taken inside and along the outer reef of British Honduras. The lighthouse keeper at Cay Bokel reported that fish apparently of these species weighing up to twenty-five or thirty-five pounds had been taken in the vicinity. At Cozumel Island several schools of blackfin tuna were sighted and three fish of about twelve pounds each were caught. Most of the schools of blackfin tunas were found from two to five miles offshore and were between islands or islands and mainland.

The kingfish (*Scomberomorus cavalla*) and its relatives, the cero (*Scomberomorus regalis*) and the Spanish mackerel (*Scomberomorus maculatus*) were well represented in the northwestern Caribbean.

Cero and Spanish mackerel of about six pounds were caught off Cape Honduras and in Trujillo Bay and some larger ones were lost. Off the Motagua River, five kingfish, ranging from six to sixteen pounds in weight, were taken in two and a half hours. At Utila Island, one or two large kingfish struck at the marlin baits and one of about eight pounds was caught by trolling along the reefs. Five Spanish mackerel were taken in a gill net set in the harbor. The rip off Cape Tres Puntas in Guatemala provided good kingfishing. Six ranging from five to fifteen pounds were taken with feather lures in about two hours of trolling.

Small cero and Spanish mackerel were abundant among the inside reefs of British Honduras and some small kingfish were also caught there. Larger cero and kingfish were taken by trolling off the outer reefs, and the lighthouse keeper at Cay Bokel said that there was a fine run of large kingfish there in the spring. Natives of Grand Cayman said that large kingfish were taken by trolling with sprats (*Sardinella sardina*) from sailing canoes and constitute an important commercial catch for the island.

No wahoo (*Acanthocybium solandri*) were caught in the vicinity of the Gulf of Honduras, but it was reported that they were occasionally taken in the offshore waters. The Hog Islands and the waters off Belize were reported to be good grounds for these fish, the best season at the latter place being in the spring and early summer.

A seven pound wahoo was caught from the "Irmay" off Grand Cayman. Natives there said that these fish, locally called "queenfish," are caught regularly and reach weights of eighty pounds or more. They attributed the poor fishing at the time of our visit to the long duration of fresh easterly winds. At the Swan Islands these fine fish appear to be relatively abundant. An eleven pounder was caught from the "Irmay" as she approached the Island, while what appeared to be a much larger one was hooked at the same time on another line but got away and soon after this a heavy handline was parted. The next morning four wahoo were hooked simultaneously and three were boated. The two largest weighed fifty-seven and thirty-six pounds respectively, while the third was only slightly smaller. Another heavy handline was parted as the party left the islands. It was unfortunate that more time could not be devoted to exploring the possibilities of these islands and that a more suitable fishing boat was not available. The wahoo took white, yellow, and red and white feathers at speeds of four to nine knots.

Blue marlin (*Makaira nigricans ampla*) and sailfish (*Istiophorus americanus*) were reported in the Gulf of Honduras region, but most of our information on these fish was obtained from local fishermen. As they make no attempt to catch these species, they are not as well acquainted with them as with the fish they catch commercially. No estimates of their abundance could be made, except that they did not appear to be plentiful in midwinter.

Trujillo was the only locality on the coast of Honduras where we found convincing evidence of the presence of billfish. An employee of the United Fruit Company has caught a sailfish and lost a marlin off Cape Honduras. Residents at Puerto Castilla had observed sailfish in Trujillo Bay and reported one which they had seen speared from the town dock. Trolling with outrigger baits in the Bay and off Cape Honduras was unproductive, but the time spent was not nearly sufficient to test the possibilities of the place. The baits were not molested by other species of fish

The Bay Islands appear to be a better fishing ground, especially for large marlin. The only certain billfish strikes were obtained about a mile or two north of Conical Hill on Utila Island. A fish believed to be a blue marlin of about 200 pounds was hooked and parted the 24-thread line after making a considerable run and two or three leaps. On the next day, a fish thought to be a white marlin (*Makaira albida*) struck, but threw the hook on its first jump. Both struck at large mullets, a bait which was rarely obtainable. On both days other strikes were obtained which might have been from billfish. About twenty hours were spent in offshore trolling at Utila and five hours at Bonacca. Off Utila smaller fish, especially barracudas, often spoiled the outrigger baits, making it virtually useless to troll them near any bank or reef and at Bonacca large quantities of floating weed continually fouled the lures.

Bay Island fishermen related many stories about marlin and showed us the bill of a sailfish they had taken. They told of a U. S. sportsman who had hooked five large blue marlin in one week fishing off Bonacca Island, but had lost all of them. They did not recall what time of year this occurred and there seemed to be no agreement as to which season was the best for this fishing.

Fishermen in British Honduras report sailfish, which they call "ocean pipers," and marlin along the barrier and outlying reefs. Among the favored localities are Columbus Reef, English Cay, Cay Bokel and Glover Reef. The lighthouse keeper at Cay Bokel said that he frequently observed sailfish, sometimes three or four at a time and also saw a very large marlin caught by handline. No billfish were raised in about twenty-five hours of trolling in these localities and off the Zapotilla Cays. The latter is an excellent looking ground with fine rips, but fishing was hampered by excessive amounts of floating weed. The best season for marlin and sailfish in British Honduras was said to be in the spring and early summer.

Natives reported large marlin, locally called spikefish, off Grand Cayman Island and sailfish off the Swan Islands and Cozumel Island, but little specific information was obtained.

Jacks were among the most common fish in many of the localities visited. In the Trujillo area, the jack crevalle (*Caranx hippos*) was very abundant. Eight, ranging from two to twelve pounds, were taken in an hour and a half of trolling off Cape Honduras. Some were also caught in the channel to the lagoon of Guaimoreto and off the mouth of a small river west of Trujillo. Off the Motagua River, twelve of these fish were boated in two and a half hours, although the very effective wire line was used only for the first few minutes. A blue runner or hardtail (*Caranx crysos*) was also taken at this place.

Among the Bay Islands jacks were not so plentiful. A large yellow jack (*Caranx bartholomaei*) was taken off Utila. Horse-eye jack (*Caranx latus*) and brown jack (*Caranx ruber*) were taken in the harbor and lagoons of this island. A brown jack and a rainbow runner (*Elagatis bipinnulatus*) were caught off the reefs of Barburata, near Roatan Island.

Off the coast of Guatemala blue runners were the only jacks taken but they were very numerous. Some were caught at Ox Tongue Light, where schools of them were seen surfacing in the rips, while others were taken off Cape Tres Puntas and en route to Punta Gorda.

In British Honduras, jack crevalles were numerous in the rivers and many were taken by plug casting or trolling in the Manatee. Some yellow jack were caught by trolling off the inner reefs and cays.

A six pound rainbow runner was taken off the Swan Islands, and a twenty-six pound amberjack (*Seriola dumerili*) was caught off Cozumel Island.

Jack crevalle struck freely at almost any lure, but in water of sufficient depth a spoon trolled on a wire line was extremely effective and in rivers we had good luck with plugs. Most of the other jacks were caught on trolled feather lures. Fifteen thread tackle was usually used for trolling, but better sport would be had with lighter gear. The jack crevalles and yellow jacks taken weighed from two to about fifteen pounds, while most of the brown and horse-eye jacks and blue runners weighed less than three pounds.

Dolphin (*Coryphaena hippurus*) were found occasionally in the northwest Caribbean. Although none were encountered along the coast of Honduras and Guatemala, four were caught in three hours of fishing off Conical Hill, Utila Island, and two were boated while trolling along the rips off the Zapotilla Cays. One was caught at the Swan Islands and two at Cozumel Island, where they were also seen leaping in spectacular pursuit of flying fish. Those caught weighed from eight to eighteen pounds each and were taken on heavy handlines or 15-thread rigs, but 9 or 6-thread tackle would be more sporting. They took strip baits trolled at five knots and feather lures trolled similarly or when cruising at nine knots.

The snook (*Centropomus undecimalis*) is plentiful in the rivers of Guatemala and British Honduras. None were taken in Honduras or the Bay Islands but little fishing was done there in waters suitable for these fish. It is probable that they could be found in some of the lagoons and rivers of these regions.

At Livingston, Guatemala, in the mouth of the Rio Dulce, there is a commercial fishery for snook. They are shipped to Guatemala City where they are a favorite table fish. The director of this fishery said that three hundred snook had been caught in the early morning of the day the party made a trip up the Dulce. On the next morning, the "Black Prince" was fishing in the harbor along with forty-five native canoes but no catches were observed. The captain of the fishing cruiser operated by the United Fruit Company reported taking very large catches of snook far up the river. Two snook, weighing three and six pounds respectively, were caught by trolling small spoons off the mouth of the Graciosa River where a Guatemalan sportsman reported taking them in considerable numbers.

In British Honduras, excellent snook fishing was found in the Manatee River where these fish were often seen surfacing among the mangrove roots, grouped with small tarpon and jack crevalles. Almost every cast with a fresh water bass plug would secure a strike from one of these species and they also hit spoons or feathers, either cast or trolled. In one day eight snook weighing from about four to twelve pounds were taken, although much of the time was spent trolling for large tarpon in mid-stream, and playing large jacks on light tackle. Snook could usually be caught, even if they were not showing, by casting or trolling close to the banks. It is probable that they are equally plentiful in other rivers of British Honduras. Fresh water plug casting rigs are ideal for this fishing.

Groupers are an important food fish in the northwestern Caribbean. None were taken along the coast of Honduras, but they were fairly numerous among the Bay Islands. A 35 pound black grouper (*Mycteroperca bonaci*)* was boated after making a leaping strike at a marlin bait off Utila Island. Commercial catches at Utila also included yellow groupers (*M. venenosa*)* and Nassau groupers (*Epinephelus striatus*), weighing less than seven pounds each. Some four or five pound tiger rockfish (*M. tigris*)* were taken by deep trolling with a large spoon on a wire line off Bonacca and Roatan Islands. A small spotted jewfish (*Promicrops itaiara*)* was caught on a small spoon trolled near the entrance of the Graciosa River in Guatemala.

The barrier and outlying reefs of British Honduras produced a good many black and yellowfin groupers. Almost all of these were taken by deep trolling along the outside of the reefs with a large spoon on the wire line, and they ranged from 8 to 26 pounds in weight. Cay Bokel in the Turneffe Islands offered the most consistent fishing for these species. Nassau groupers were also caught occasionally in the waters of this colony.

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*Tentative identification

Snappers also form an important part of the commercial catch in the northwest Caribbean. On the coast of Honduras we encountered the grey snapper (*Lutianus griseus*) the school-master (*L. apodus*)*, the muttonfish (*L. analis*) and the black snapper (*L. cyanopterus*). A thirty-eight pound specimen of the last species was caught on a trolled surface plug in the inlet to the lagoon of Guaimoreto.

Among the Bay Islands, some yellowtails (*Ocyurus chrysurus*) were taken by trolling feather lures, and schoolmasters and muttonfish were seen among the commercial landings. Handliners fishing in deep water took some vermilion snappers (*Rhomboplites aurorubens*)*, a fish called "salmon" (*Etelis oculatus*)* and red snappers of a species not determined.

In the waters of British Honduras, some muttonfish, yellowtails, and a dog snapper (*Lutianus jocu*)* were taken among the reefs and cays, and a 30 pound black snapper was caught on a trolled swimming plug in the Belize River. Lane snappers (*Lutianus synagris*) were occasionally seen among commercial catches.

PART II. VICINITY OF CARMEN, CAMPECHE, MEXICO

A survey of the sport fishes in the vicinity of Carmen, Mexico, on the Gulf of Campeche, was made from March 6 to March 26, 1950. The party comprised Col. John K. Howard, of the Harvard Museum of Comparative Zoology, Dr. Raymond A. Gilmore of the U. S. Fish and Wildlife Service, and the author, representing the Woods Hole Oceanographic Institution. While there the party collected many species of the local fish fauna for future study.

Most of the sport fishing was done with rod and reel from a boat chartered from Senor Miguel A. Manjarrez, the local representative of the Department of Fisheries of the Mexican government, who also provided a large beach seine. While only two hauls were made with this gear, one of them, made in a small lagoon at the northwest corner of Carmen Island, was very successful. Thanks are extended to Don Pedro Palazuelos who invited the party to spend a day on one of his shrimp boats and select specimens from the catch. He also presented the party with a collection of fish from another of his boats, and furnished much other assistance. Gratitude is also expressed to Mr. Lewis Frank for donating working space in his shrimp processing plant, and to Mr. Torquato Paz of La Aguada, who was most helpful in arranging purchases from local fishermen and in guiding the party.

There follows a description of the sport fishing possibilities for the various species which were encountered at the time of the sojourn. Other game fish which were seen in the markets or reported by residents are included in a list at the end of the paper. Fish which are of no sporting interest have been omitted.

Carmen is becoming famous for its tarpon fishing. These fish appeared to be extremely numerous in this area, although their average size may not be as great as in some other well known tarpon grounds.

The many rivers and passes in the Laguna de Terminos offer a wide choice

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*Tentative identification

COMMON NAME	SCIENTIFIC NAME	COAST OF HONDURAS		BAY ISLANDS		GUATEMALA		BRITISH HONDURAS		GRAND CAYMAN ISLAND		SWAN ISLANDS		COZUMEL ISLAND	
		1	2	1	2	1	2	1	2	1	2	1	2	1	2
Amberjack	*Seriola dumerili*													x	
Arnillo	*Apsilus dentatus**			x											
Barracuda	*Sphyraena barracuda*	x		x		x		x				x			
Black grouper	*Mycteroperca bonaci**			x				x							
Black snapper	*Lutjanus cyanopterus*	x						x							
Blackfin tuna	*Parathunnus atlanticus*	x		x				x						x	
Blue marlin	*Makaira nigricans ampla*		x	x					x		x				
Blue runner	*Caranx crysos*	x				x									
Bonefish	*Albula vulpes*	x		x				x							
Brown jack	*Caranx ruber*	x		x											
Cachuco	*Etelis oculatus**			x											
Cero	*Scomberomorus regalis*	x						x						x	
Croaker	*Micropogon sp.*							x							
Dog Snapper	*Lutjanus jocu**							x							
Dolphin	*Coryphaena hippurus*			x				x				x		x	
False albacore	*Euthynnus alletteratus*	x		x				x							
Grey snapper	*Lutjanus griseus*	x													
Hogfish	*Lachnolaimus maximus*			x											
Horse-eye jack	*Caranx latus*	x		x				x							
Jack crevalle	*Caranx hippos*	x						x							
Jolt head porgy	*Calamus bajonado**							x							
Kingfish	*Scomberomorus cavalla*	x		x		x		x			x				
Lane snapper	*Lutjanus synagris*							x							
Mako shark	*Isurus oxyrinchus*								x						

* Tentative Identification
1 Taken or seen
2 Reported but not seen

Common Name	Scientific Name	Coast of Honduras		Bay Islands		Guatemala		British Honduras		Grand Cayman Island		Swan Islands		Cozumel Island	
		1	2	1	2	1	2	1	2	1	2	1	2	1	2
Margate fish	*Haemulon album*								x						
Muttonfish	*Lutjanus analis*	x		x				x							
Nassau grouper	*Epinephelus striatus*			x				x							
Permit	*Trachinotus goodei*			x											
Rainbow runner	*Elagatis bipinnulatus*			x					x			x			
Red hind	*Petrometopon cruentatus*			x				x							
Red snapper	*Lutjanus sp.*			x											
Reef jack	*Seriola falcata*			x											
Round pompano	*Trachinotus falcatus*							x							
Sailfish	*Istiophorus americanus*		x		x				x				x		x
Schoolmaster	*Lutjanus apodus**	x		x											
Spanish mackerel	*Scomberomorus maculatus*	x		x				x							
Snook	*Centropomus undecimalis*		x		x	x		x							
Spotted jewfish	*Promicrops itaiara*					x		x							
Tarpon	*Tarpon atlanticus*	x			x	x		x		x					
Ten-pounder	*Elops saurus*		x					x							
Tiger rockfish	*Mycteroperca tigris**			x											
Vermillion snapper	*Rhomboplites aurorubens**			x											
Wahoo	*Acanthocybium solandri*		x		x				x	x		x			
White marlin	*Makaira albida*			x											
Yellow jack	*Caranx bartholomaei*			x				x							
Yellowfin grouper	*Mycteroperca venenosa**			x				x							
Yellowtail	*Ocyurus chrysurus*			x				x							

* Tentative Identification
1 Seen or taken
2 Reported but not seen

of fishing spots to the tarpon enthusiast. Among the most popular is the Eastern Entrance or Barra Aguada, which at times is full of schools of surfacing tarpon (*Tarpon atlanticus*). The party took several fish there ranging from twenty to fifty pounds, by trolling, and no larger ones were seen.

Larger tarpon were found in the arm of the lagoon east of Aguada leading to Sabancuy. One fish weighing slightly over fifty pounds was boated and several which looked larger were lost.

Another excellent tarpon ground is on the Candelaria River at Polvoshal Ranch. The party trolled there for only about an hour, but fish were rising and striking steadily and two, weighing twenty-five and forty pounds respectively, were caught. Another party of fishermen reported catching about twenty tarpon in one day at this place and these were also of a medium size.

The best tarpon fishing found in the western part of the lagoon was at Boca Chica, a narrow passage which connects a small lagoon fed by two large rivers with the main one. Tarpon in the main channel appeared to run from twenty-five to over a hundred pounds. A smaller channel was frequently full of little tarpon near its entrance to the main passage.

The tarpon ground nearest to the city of Carmen is at the northwest corner of Carmen Island. When tide and wind are proper, a fine rip makes up. One day some very large tarpon were seen leaping and two of them struck at plugs cast from the beach for snook. On the next day smaller fish were showing and five strikes were secured in quick succession by trolling among them. On other days there was no sign of fish. Undoubtedly many other tarpon habitats could be found by anglers with a suitable boat and sufficient time.

Most of the fish taken trolling were caught on feathers, yellow ones apparently being preferred, but they also struck well on spoons. While only artificial lures were used, other anglers used small fish successfully as trolling baits.

Tarpon struck well at casting lures, especially Pikie Minnows and Husky Pikies. The silver flash color or white and silver with red head were very effective, and the blue mullet scale was also good.

Barracuda (*Sphyraena barracuda*) are not as plentiful in the vicinity of Carmen as in the Caribbean and among the Bahamas. Some inhabit the reef on the west side of the Eastern Entrance of the Laguna de Terminos and the entrance to the arm of the lagoon leading to Sabancuy. In the shallow waters of the latter place a thirty pounder put up a spectacular fight when taken on a light rod with 9 thread line. The barracudas caught here averaged about twenty pounds in weight. One weighing fifty-five pounds was reported to have been caught while the party was at Carmen.

The barracuda took feather lures rigged as for tarpon with 9/0 O'Shaughnessy hooks. The outfits used were 15 thread and 9 thread, the latter, of course, being more sporting.

A few Spanish mackerel (*Scomberomorus maculatus*) were caught in the vicinity of Carmen on trolled feather lures. These ranged from two to six pounds in weight, as did the few seen in the market. There was no indication that these fish were abundant at the time of this survey.

Jack crevalle (*Caranx hippos*) were extremely abundant in the Carmen area. About twenty of these fish, averaging fifteen pounds in weight, were caught from a shrimp boat by trolling and by throwing a baited hook alongside from the stern. In the latter case, the jacks would dart out from under the boat and seize the bait as it sank by the stern. Small fish caught in the shrimp nets were used for bait, and the big jacks could be seen following the nets to the surface and feeding on escaping or discarded fish and crustacea.

Schools of these fish were observed in rivers and inlets, especially at tide rips. They struck trolled feather lures and spoons, usually being caught on tarpon tackle although they would provide better sport on lighter gear.

The only other jacks observed were blue runners, (*Caranx crysos*) which occasionally appeared in small numbers in the market.

Good snook fishing was found in the rip at the northwest corner of Carmen Island. One of the party took nine of these fish, ranging from four to twelve pounds, in one hour of casting from the beach into this rip. A regular fresh water plug casting rig with eighteen pound test line and a silver flash Pikie Minnow proved to be an effective and very sporty means of taking these leaping fighters. About a bushel of small snook (*Centropomus undecimalis*) was taken in a beach seine haul in the small lagoon nearby, and one was caught by plug casting at its inlet. Residents of Carmen catch a few snook from the docks at night, using handlines with shrimp for bait and chum.

Spotted jewfish (*Promicrops itaiara*) are fairly common in the region. One weighing about twelve pounds was taken in the arm of the lagoon leading to Sabancuy, and the capture of a hundred pounder by a native fisherman was witnessed at Boca Chica. Much larger ones are reportedly taken. Two small red groupers (*Epinephelus morio*) were caught by bottom fishing in the Gulf off Santa Rosa. Few groupers were seen in the market.

The black snapper (*Lutjanus cyanopterus*) is of interest to sport fishermen mainly because of its large size and willingness to take trolling lures. A thirteen pounder was caught on a feather lure in the Eastern Entrance, and a Texas sportsman donated to the collection a sixty-eight pounder taken there on the same day. The capture of a sixty-four pounder in the Candelaria River was also reported. Other species of snappers are taken by native fishermen, including the muttonfish (*Lutianus analis*), the grey snapper (*L. griseus*), the lane snapper (*L. synagris*) and the red snapper called guachinango, which is the most highly prized.

About half a bushel of spotted weakfish (*Cynoscion nebulosus*), up to four

CAMPECHE, MEXICO — Fish taken or seen

Common Name	Local Name	Scientific Name
Barracuda	Picuda	*Sphyraena barracuda*
Black drum	Tambor	*Pogonias cromis*
Black snapper	Pargo mulato	*Lutjanus cyanopterus*
Blue runner	Cojinua	*Caranx crysos*
Croaker	Roncador	*Micropogon sp.*
Grey snapper	Pargo mulato	*Lutjanus griseus*
Jack crevalle	Jurel	*Caranx hippos*
King whiting		*Menticirrhus americanus**
Lane snapper		*Lutjanus synagris*
Muttonfish	Pargo rubia	*Lutjanus analis*
Red grouper	Mero	*Epinephelus morio*
Red snapper	Guachinango	*Lutjanus sp.*
Round pompano		*Trachinotus falcatus*
Sand squeteague		*Cynoscion arenarius**
Snook	Robalo	*Centropomus undecimalis*
Spanish mackerel	Macarel	*Scomberomorus maculatus*
Spotted jewfish	Cherna	*Promicrops itaiara*
Spotted weakfish		*Cynoscion nebulosus*
Tarpon	Sabalo	*Tarpon atlanticus*
Triple-tail		*Lobotes surinamensis*
	Reported but not seen	
Ten-pounder	Macabi	*Elops saurus*

pounds in weight, was taken in a beach seine haul in the small lagoon on the northwest corner of Carmen Island. Mr. Cecil Branson of Carmen reported that they also frequented a cove on the south side of the island. Some smaller sand squeteague (*Cynoscion arenarius*)* were caught in the nets of the shrimp boats, as well as small croakers (*Micropogon*) of various species some of which were also caught in the beach seine. A few king whiting (*Menticirrhus americanus*)* weighing less than two pounds were also taken by the shrimp boats.

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* Tentative identification

Contribution No. 612

THE GULF STREAM SYSTEM *

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(Read April 25, 1952)

ALTHOUGH the scientific history of the Gulf Stream was reviewed recently by Stommel (1950), so much field work has been carried out since then that today there is a good deal that can be added to his excellent account of the gradual evolution of our understanding of the problems presented by this most spectacular of ocean currents.

Since the pioneering study of Benjamin Franklin (1786), there have been three main observational approaches to the problems of the Gulf Stream. The first was the statistical approach and, until very recently, this was limited to surface observations. Through the leadership of Matthew Fontaine Maury, surface temperature observations and reports of surface currents experienced by navigators have been collected during the last century in ever-increasing quantities. These data were averaged by season and later by month, and also, as they increased in quantity, by smaller and smaller units of area. The most modern example of such a statistical picture of the surface characteristics of the Gulf Stream was published by Fuglister (1947). This is the sort of information shown in atlases of the ocean and is the basis of the generally accepted view that the Gulf Stream gradually broadens and weakens as it flows northeastward from Cape Hatteras toward the southern limits of the Grand Banks. As we shall see, and as was indeed pointed out by Fuglister, there are serious limitations to the statistical approach, for northeastward from Cape Hatteras the average Gulf Stream bears little resemblance to the one existing at any given time.

The second approach, which was employed vigorously during the 1930's, was to observe in cross section the distribution of temperature and salinity down to depths of 2,000 meters or more. As the theory predicted for steady state conditions, it was found that the cross current density gradient at any depth was in approximate balance with the Coriolis forces that might be expected to accompany a reasonable velocity profile. In the Straits of Florida at least, a velocity profile had been secured by direct observation and, as was shown by Wüst (1924), this agreed very well with the velocities and transport that could be computed from the observed cross current distribution of temperature and salinity under the assumptions of the Circulation Theorem. The many cross sections of the Gulf Stream off southern New England that were secured during the 1930's (Iselin, 1940) could, therefore, be interpreted with some assurance in terms of subsurface velocity and total transport, although subsurface current observations were only available from the Florida Straits. The net result of these temperature and salinity profiles was to show that the current was considerably narrower and swifter than indicated by the statistical surface charts, that it varied in transport seasonally, and perhaps over longer periods, and that major disturbances, possibly large eddies, were commonly present on either side of the current.

After World War II, when field observations could again be resumed, two new tools were available, which permitted a quite different approach. The greatly improved navigation afforded by Loran made it possible to estimate continuously the direction and velocity of the surface current being encountered by the research vessel. Thus, it was possible to maneuver in and out of the current on short tacks so as to track some features of it for considerable distances in the downstream direction. Furthermore, the development of a diving thermometer that could be used underway permitted the continuous observation of temperature down to a depth of 300 meters. The usefulness of these new techniques was first reported by Iselin and Fuglister (1948). It was soon shown that a major and hitherto unexpected feature of the Gulf Stream northeastward from Cape Hatteras was its meanders. Moreover, the current was again shown to be narrower and swifter than had been generally believed possible.

Almost simultaneously, von Arx (1950) developed a new and powerful method of observing

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surface currents from a ship underway. This depended on the electric potentials induced by the movement of the water through the earth's magnetic field.

In June 1950, it became possible to employ six ships simultaneously during a three-week period for a coordinated survey of the Gulf Stream between Cape Hatteras and the Grand Banks. All three new techniques; namely, Loran Navigation, the bathythermograph, and the geomagnetic electric kinetograph, were exploited to the utmost. Some of these results were recently reported by Fuglister and Worthington (1952), and by von Arx (in press). The six-ship survey, known as Operation Cabot, which was organized and directed by the U. S. Hydrographic Office, besides confirming the general conclusions of the previous single-ship surveys, showed that the waves forming just east of Cape Hatteras as they develop into meanders move slowly downstream and the details of the detachment of a large offshore meander south of Halifax were observed during a twelve-day period. Perhaps even more significant was the indication that two distinct Gulf Streams passed the tail of the Grand Banks.

By this time the modern students of the Gulf Stream had become thoroughly puzzled. On theoretical grounds, Stommel (1948) and Munk (1950) had been able to show that narrow swift currents were to be expected in the western part of each ocean, and Haurwitz and Panofsky (1950) were more or less able to account for the development of the meanders eastward from Cape Hatteras, but none of the available theory in any way suggested that a second warm current might develop north of the primary Gulf Stream.

In June 1951, this new feature was followed from off southern New England eastward to the Grand Banks area so that there is no longer any doubt that it is a continuous warm current, rather than a series of clockwise eddies, which one encounters along the Nova Scotian continental slope. In fact, the 1951 observations suggest that a third and similar filament of warm water develops inside this one as it crosses over to the Grand Banks. Thus, it is now thought that eastward from Cape Hatteras the warm water does not flow as a single current, but as a series of everlapping currents arranged somewhat like the shingles on a roof. In some manner, as yet by no means fully understood, the countercurrent along the inshore edge of Gulf Stream No. 1 drains off warm water and momentum, and transfers it to Gulf Stream No. 2, just to the north. Further eastward this in turn supplies Gulf Stream No. 3. Data gathered last summer by *Albatross III* east of the Grand Banks indicate that this process may continue to at least mid-ocean and possibly farther. Thus, it is indeed fortunate that of recent years we have begun to speak of the Gulf Stream System, for the old statistical Gulf Stream is not one gradually widening and weakening current, but a series of overlapping, narrow, swift streaks of flow.

The original need for the term Gulf Stream System was that on a statistical basis the Gulf Stream appeared to branch after passing the tail of the Grand Banks. Three main branches seemed to be involved (Iselin, 1936). We now see that this process has its origins well to the westward of the Grand Banks and that it is not really branching in the ordinary sense, but the development of a series of new currents, each to the north of the older ones. Much the same phenomena seem to be present in the jet streams found at high elevations in the great belts of prevailing westerly winds of mid-latitudes, although each atmospheric jet has greater dimensions than the overlapping subdivisions of the Gulf Stream System.

It must be admitted that considerable uncertainty still exists in the proper contouring of the recent temperature surveys. Proceeding at the rate of about 200 miles a day, and without any clear picture of what lies ahead, the oceanographer cannot so choose his courses on the basis of the observed temperature and surface current that there can be but one interpretation of the survey. If he follows each minor loop encountered, he cannot develop the larger picture. On moving from warm water to colder water and then back to warm water again, he does not know for certain that he is back in the same warm current. He may have found a new warm streak or an isolated eddy. To overcome this basic difficulty, it is hoped that in the near future means can be developed to observe surface temperature from a plane. At 1,500 miles a day, the interpretation of Gulf Stream temperature surveys should be much less uncertain, especially if a plane and a ship can be used together. Once the basic pattern of the Gulf Stream System has been worked out and once we know more about the rate of change of this pattern, the ship can be used again with confidence to develop details and to extend the survey into the third dimension.

Now, what can be said about the rate of change of the complicated pattern of flow making up the Gulf Stream System? Operation Cabot showed that a period of about ten days is required to produce as much change as occurs ordinarily in one day in the swift currents of the upper atmosphere. This is, of course, only one observation, but it seems reasonable in view of the huge amounts of momentum involved in ocean currents and their relative slowness compared with the winds, that changes in what might be termed "the weather map of the ocean" would be much slower than in the atmosphere. Thus, the synoptic oceanographer, when he comes into being, will perhaps have an easier or at least a more leisurely task than the weather forecaster.

To understand a phenomenon as huge and complicated as the Gulf Stream System, we must first be able to describe it accurately. Thus, for some years to come field observations must be continued and means must be developed to secure continuous data at a few critical points in the system, at least. If the past is any guide, theory will probably continue to lag behind the observational approach. However, a beginning has been made on at least one additional possible attack on the problems of the Gulf Stream. At the Woods Hole Oceanographic Institution, using funds supplied by the Office of Naval Research, a large, rotating, paraboloidal basin has been set up in the hopes of learning how to reproduce North Atlantic circulation on a model scale. In this model, which has been designed by Mr. William von Arx, the effects of the earth's rotation on currents moving through a considerable range in latitude are for the first time correctly scaled. While there are serious difficulties to be overcome, the model Gulf Stream System sufficiently resembles the prototype so that it is already clear that this new technique has great possibilities. Even if the model fails in reproducing the full complexities of the prototype, it should be extremely helpful to the theoreticians, for there is little doubt that the model can handle correctly the more simplified situations that mathematical studies can hope to formulate.

Obviously, physical oceanography still has a long way to go before oceanic circulation is thoroughly understood. Nevertheless, having recently broken away from studies of the unreal, average ocean, we can expect rapid progress to continue during the next few years.

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Contribution No. 613

THE HISTORY OF THE PREVENTION OF FOULING

By

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Official U. S. Navy Photograph

THEY ARE PROTECTED BELOW THE WATERLINE TOO

This 1947 aerial view of the Naval Reserve Fleet Berthing Area, Charleston, S. C., shows part of the "Mothball Fleet." Such preservation of ships is just part of the battle. Centuries of experiment and research have gone into developing means for keeping ship's hulls free from fouling. Modern U. S. Navy methods can keep vessels like these operating for as long as eighteen months with no reduction in speed or increase in fuel consumption caused by fouling.

THE HISTORY OF THE PREVENTION OF FOULING*

By FREDERICK B. LAIDLAW

The effects of fouling have only recently been subject to systematic scientific inquiry. Its seriousness, however, has been recognized from very ancient times. Although written records of the treatment of ship bottoms as early as the 5th century B. C. have been found, the search for an antifouling surface undoubtedly began with even earlier ships about which we have little information.

Historically, the development of these surfaces falls readily into three parts: (1) the repeated introduction and use of metallic sheathing, culminating in the discovery of copper sheathing as an effective antifouling surface; (2) the invalidation of the use of metallic copper on iron hulls because of galvanic effects, which followed the development of iron ships; and (3) the eventually successful efforts to devise antifouling paints that, in the case of iron or steel hulls, could be applied over an anticorrosive coating.

Numerous other antifouling devices were continually being tried or suggested. In periods of peace, the tendency has been to use the current antifouling system regardless of its efficiency. Periods of war have always intensified experimental investigation.

EARLY SHIPBOTTOM SURFACES

The history of both ships and sea power is older than written records, some of the great maritime nations of the ancient world being known to us only through the records of a later period. But even the earliest records, although they say little or nothing about shipbottom treatment, tell of large fleets and big ships, of long voyages and naval battles. We can assume, therefore, that fouling was a problem to ancient ships, even though we do not know what measures were taken against it.

The early ships and fleets were larger, and the voyages longer, than is generally realized. Ancient Egyptian ships were sometimes 160 feet long and traded as far as the land of Punt (Somaliland). The Phoenicians in 1000 B. C. were reputed to have circumnavigated Africa, voyaged to Cornwall in Britain for tin, and as early as the 6th century B. C. explored the west coast of Europe. Early sea fights involved fleets of hundreds, and sometimes thousands, of ships. While the warships of the ancient world were often intended to be beached, or even transported overland, the merchant ships were not and were correspondingly larger. An Egyptian corn ship at Piraeus in Roman times was described by Lucian as "180 feet long, over a quarter of that in width, and 44 feet from deck to keel;[1] with a crew like a small army, and carrying as much corn as would feed every soul in Attica for a year."

The earliest mention of fouling that we have found is a casual reference to it in connection with the Echeneis or Remora; the fabled "ship-stopper." This comparatively small fish, mentioned by Aristotle as early as the 4th century B. C., is credited by both ancient and modern writers with being able to slow down ships going at full speed, or even to stop them entirely as if they were tied to one spot in the ocean. In commenting on this belief, Plutarch pointed out that fouling rather than the Echeneis might be responsible. He stated that it was usual to scrape the weeds, ooze, and filth from the ships' sides to make them go more easily through the water. In 1559 Laevinus Lem-

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* EDITOR'S NOTE:—This article (Contribution No. 613, Woods Hole Oceanographic Institution) is a chapter from the forthcoming U. S. Naval Institute book, *Marine Fouling and Its Prevention*. The result of millions of dollars of research, this book will be invaluable to shipbuilders, the marine industries, and everyone who owns or operates a ship or small craft.

[1] This ship, the *Goddess Isis*, was not unusually large; other Roman corn ships were up to 200 feet long. As a comparison, the U.S.S. *Constitution* was 174 feet 10 inches on the main deck.

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nius wrote "shell-fish and a little fish called Echeneis stick so fast that they will stop ships, and hinder their courses, therefore our men use to rub them off with sharp brushes, and scrape them away with irons that are crooked for the purpose, that the ship being tallowed and careened well and smoothly may sail the faster."

The ancient Phoenicians and Carthaginians were said to have used pitch and possibly copper sheathing on their ships' bottoms. Wax, tar, and asphaltum also have been used from very early times. We can not be certain of the purpose of these surfaces even in later times when written records exist. While it is probable that some of them were at least in part an attempt to prevent fouling, they may also have been applied for water-tightness, to achieve a smooth surface, for structural strength, or, particularly in the case of metallic sheathing, as protection against ship worms.

There is a record of the use of arsenic and sulfur mixed with oil in 412 B. C. The Greeks are known to have used tar or wax, and, at least as early as the 3rd century B. C., lead sheathing. The wax was applied hot and was burnt into the hull with hot irons, a process that became known as "encaustic" or as "ship-painting." According to Pliny, coatings of this nature applied to vessels "will never spoil from the action of the sun, winds, or salt water." When lead sheathing was used, it was attached to the ship's hull with copper or gilt nails, usually over an insulating layer of paper or cloth. According to Chatterton, this suggests strongly that the corrosive effect of lead on iron, which finally forced the discontinuance of lead sheathing altogether, was recognized even then.

In spite of its corrosive action, lead sheathing was perhaps the material most frequently tried for the protection of ship bottoms prior to the 18th century. Repeated attempts to use it had been made from the time of the ancient Greeks. The ships of Archimedes of Syracuse (287–212 B. C.), for example, were sheathed with lead and fastened with heavy copper bolts. The Romans also used lead sheathing, and several of their ships, with the lead sheathing intact, have been recovered within comparatively modern times.

Although forgotten for several centuries, lead was used in 15th century England. In the reign of Henry VI (1421–1471), a report of a ship sent on a voyage of discovery records as an " invention" that "they cover a piece of the Keeles of the Shippe with their sheets of Leade, for they have heard that in certain partes of the ocean a kind of wormes is bredde which many times pearseth and eateth through the strongest oake that is." While lead sheathing is a poor antifouling surface, it would be, as this 15th century report suggests, a good protection against ship worms. This report suggests, also, that in England lead sheathing was not usually used at that time. Its use was said to be copied from contemporary Spanish ships.

Leonardo da Vinci designed a rolling mill in 1500 for making sheet lead. Early in the 16th century, Spain officially adopted lead sheathing, and its use spread to France and England. In the reign of Charles the Second (1660–1685), a monopoly was granted to Howard and Watson for the use of milled lead for sheathing; and it was ordered that no other sheathing be used on His Majesty's ships. Accordingly, the *Phoenix* and some twenty other ships were sheathed with lead fastened with copper nails. Shortly after, however, complaints were made of the corrosive effect of lead on iron,[2] the *Plymouth* and other ships having had their rudder irons so eaten as to make it unsafe for them to go to sea. In 1682, a commission was appointed to make an investigation, and on the basis of its report, lead was officially abandoned by the Admiralty.

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[2] Lead was also reported to be too soft to stay on the hull, and many objected to its dead weight.

In spite of the commission's findings, rollers for milling lead into sheets for sheathing were patented in 1687. Even after the successful introduction of copper sheathing in 1761, lead was still occasionally tried. In 1768, the *Marlborough* was sheathed with lead; but two years later, when she was docked at Chatham, the iron fastenings were found to be so deeply eaten away that the lead was stripped off and replaced with wooden sheathing.[3]

In the time of Henry VIII (1509–1547) and during the 17th century, wooden sheathing was put on over a layer of animal hair and tar. This was reported to prevent the worms from penetrating to the planking, although it greatly increased the cost of building.[4] An outer wooden sheathing was not new. Although it is said to have been introduced by Hawkins under Queen Elizabeth, it appears to have been used in the 15th century. In the 18th century, after lead, with which it apparently alternated, had been pronounced a failure, wood sheathing was again in general use. It was sometimes filled with iron or copper nails having large heads, put in so closely that the heads were touching and formed a kind of metallic sheathing. This wooden sheathing also was often painted with various mixtures of tar and grease; with sulfur, oil, "and other ingredients"; or with pitch, tar, and brimstone.

Other early shipbottom surfaces besides wood or lead sheathings were also recorded. The Vikings of the 10th century A. D., although they generally painted their boats above the water line, used nothing on their ships' bottoms. They tell in one of their sagas, however, of a small boat that was protected from the worms by "seal tar." In Aragon, a sheathing of hides was used in the 14th century. Pitch was commonly used from the 13th to the 15th centuries, sometimes mixed with tar, oil, and resin, or with tallow. The great Venetian fleets of the 15th century used tar.

Morison, in his life of Columbus, says that the ships' bottoms of that period were "covered with a mixture of tallow and pitch in the hopes of discouraging barnacles and teredos"—in spite of which the vessels had to be careened every few months to have the marine growths removed. In the time of Vasco da Gama (1469–1524), the Portuguese charred the outer surface of the ship's hull to a depth of several inches; and several centuries later, in 1720, the British built at least one ship, the *Royal William*, entirely from charred wood.

With the discovery of the antifouling qualities of copper sheathing, however, and the subsequent widespread use of copper, these earlier shipbottom surfaces fell quite generally into disuse.

Copper Sheathing

The first successful antifouling surface to receive general recognition was copper sheathing. Although it has been stated that copper sheathing was used in ancient times, the evidence is not clear, and its use as sheathing on ships' bottoms is denied by some authorities. The actual ships that have been recovered have been lead sheathed. The first certain use of copper on ships seems to have been in the bronze-shod rams of the Phoenician warships and as copper fastenings in the Greek and Roman boats, rather than as antifouling surfaces.

More extensive early use of copper is certainly possible. Prehistoric civilization knew copper and had shown great technical ability in casting and working copper and bronze for statues and other art work. Copper foundries of the 10th century B. C. have been excavated. Copper and tin were a staple in trade in 800 B. C., and the need for tin with which to make bronze was one of the chief reasons for the early voyages to Britain.[5] Thin sheets of copper were known to be in use for roofs from the 12th to the 15th centuries. However, no authentic case of sheathing ships with copper prior to the 18th century has been established. If copper sheathing was known to the ancients, it is difficult to understand why its use was lost while that of lead sheathing persisted.

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[3] Hay differs in saying that the *Marlborough* was docked, not at Chatham, but at Sheerness, where the lead sheathing was found to have been nearly all lost due to its softness.

[4] It was also believed to increase the ship's resistance. In 1668, the officers of a fleet under Sir Thomas Allen fitting out to attack the Algerians petitioned that they might not have their vessels "so encumbered" (with sheathing) as they would be unable to overtake the light-sailing unsheathed vessels of the enemy. A letter from Holland in 1666 pointed out that "the hair, lime, etc. does not altogether affright the worms while it much retards the ship's course."

[5] Alexander the Great (336–323 B.C.) demanded as tribute from the Kings of Cyprus "brass or copper, flax and sails" with which to equip a fleet.

The use of copper as an antifoulant was suggested as early as 1625, when a patent was granted for a composition that very probably contained some form of copper. In 1728, another patent was obtained for "a new method of sheathing and preserving the planks of ships," consisting of "rooled" copper, brass, tin, iron, or tinned plates, although no record of its immediate use has been found. Later in the 18th century, wooden sheathing was filled with copper nails whose heads touched each other. In spite of these desultory efforts, apparently it was not until the experiment of H.M.S. *Alarm* that the antifouling qualities of copper were recognized.

In 1758 H.M.S. *Alarm*, a 32-gun frigate, was sheathed with thin copper "for an experiment of preserving it against the worm." This first authenticated use of copper sheathing was, therefore, probably as a substitute for lead or wood sheathing, and largely for protection against ship worms.

A report on the *Alarm* took note of the plates washed off the bow of the ship where they were exposed to the full force of the sea, and the amount of waste due to the wear of the water. It recorded the soundness of the planking except for one spot that had been rubbed bare at the start of the voyage. It remarked on the freedom of the bottom from fouling, except on the rudder where iron nails had been used purposely to vary the experiment. It notes, with surprise, the corrosion of the iron where it had contacted the copper. Finally, it compared the cost of the copper with the cost of wooden sheathing, finding them about equal.

The report stated three conclusions: that copper was a protection against worms, that it did not injure the planking, and that it did not foul. These advantages were considered so important that further experiments were recommended in which thicker plates and copper nails were to be used throughout; the copper to be insulated from, or kept at a distance from, the iron.

A second ship, the *Aurora*, was coppered by the British Admiralty in 1765; a third, the *Stag*, in 1770; four more in 1776; and nine in 1777.[6] Within the next three years the use of copper became general throughout the British Navy. In 1779, the British felt that it would enable them to overtake the faster sailing French vessels that were subject to fouling. By 1789, two boats had been built in England entirely of copper, "without any planking whatever."

The first American naval vessel to be coppered was the frigate *Alliance*. This was done in 1781. The ships built under the Naval Act of 1794 for the United States Navy were also coppered. The *Constitution* was sheathed in 1795 with copper imported from England. Robert Fulton's submarine, built on the Seine for Napoleon in 1801, was also copper covered. The clipper ships of 1843–1869, and the later American whalers were coppered as a matter of course.

Although copper was the best antifouling surface known, it was by no means perfect. Its antifouling action was not always certain; and its corrosive effect on iron nearly caused it to be discontinued by the British Navy within a few years of its adoption. Although this was corrected by the use at first of mixed-metal and later of copper bolts, its excessive rate of wear proved a heavy expense. To reduce this expense as much as possible, the British Admiralty started the manufacture of copper sheathing at Portsmouth dockyard in 1803, re-working old copper sheathing and experimenting with different copper ores, and with ways of treating them. In 1823, they sought the advice of the president and council of the Royal Society to determine the best method of manufacturing copper and of preventing, if possible, its excessive wear.

In 1824, Sir Humphry Davy read two papers before the Royal Society detailing the results of his experiments on these questions.

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[6] Robert Bushnell's submarine is said to have been foiled in its attack on H.M.S. *Eagle* in New York harbor in 1776 because the copper sheathing prevented the penetration of the screw with which the explosive charge was to have been attached to the ship's bottom. Another account attributes the failure to the screw striking an iron bar.

He showed that the corrosion was due, not to the impurities in the copper as had been supposed, but to the sea water reacting with it. Knowing that copper was weakly positive in the electro-chemical scale, he considered that if it "could be rendered slightly negative, the corroding action of sea water upon it would be null." This he accomplished by attaching pieces of zinc, tin, or iron to the copper. By experiment, he found that a piece of zinc as small as a pea would protect 50 square inches of copper from corrosion; and that this was true regardless of the shape of the copper or of the position of the zinc upon it. After several experimental trials, the Admiralty adopted Sir Humphry Davy's protectors for ships in service, using cast iron surfaces of an area equal to 1/250 of the copper surface.[7]

The problem was not solved, however, for the protected copper fouled badly. Davy pointed out that the protectors prevented the solution of the copper through galvanic action, and that this was the reason why it fouled. He was thus the first to relate the antifouling action of copper to its rate of solution.

In 1831, after experimenting with shifting protectors, and protectors of mixed-metal, it was decided to use them only on ships lying in harbor. Shortly after, even this was abandoned, although experiments were still carried on with various foreign copper ores in the search for a more durable material. The loss of copper was a serious expense, but it was felt that this was fully compensated for by the protection against teredos and fouling.

The introduction of iron hulls invalidated the use of copper sheathing because of the corrosive action of copper on iron. Throughout the 19th century, therefore, and in spite of the growing importance of iron in shipbuilding, it was frequently seriously suggested that a return be made to wooden ships that could be coppered. Even late in the century most warships and other ships that had to be at sea for long periods were still built of or sheathed with wood for that reason alone.

THE PROBLEM OF PROTECTING IRON HULLS

Iron hulls, appearing late in the 18th century,[8] developed so rapidly that in 1810 Sir Samuel Bentham proposed in Parliament that the British Admiralty start building ships of iron. At that time, however, there was widespread prejudice against the use of iron, which had not proved altogether satisfactory in shipbuilding, and the motion was voted down. Nevertheless, expensive repairs, a serious scarcity of wood, and the introduction of steam engines were already forcing the change from wood to iron.

Wooden ships were limited in size and strength, and, even with improved methods of construction, could not compete economically with iron ships. Repairs frequently amounted to more than the original cost. Occasionally a ship had to be broken up because of dry rot without making even one sea voyage. The need for proper shipbuilding timbers was acute, and the lack of them often caused long delays, even to badly needed war ships. Nor were the large wooden ships strong enough to support the vibration of the early engines or the propellers. It is questionable whether any of them could run their engines at full speed without serious results.[9]

In spite of this, it was not until the middle of the century that the terrible destruction caused to wooden ships by explosive shells at Sinope in 1853, and the success of the French armored floating batteries at Kinburn in 1855, finally proved to the Admiralty the necessity for iron ships. But aside from prejudice, there were two serious objections to the use of iron hulls: corrosion and fouling.

Early in the history of iron ships, it was found that copper sheathing could not be used because its electrolytic action corroded the hull dangerously. Among many similar cases, H.M.S. *Jackal* foundered at Greenock from the corrosion having eaten through her plates, apparently unnoticed; and H.M.S. *Triton*, in 1862, had her plates corroded to such paper thinness that, according to her commander, she was only kept from foundering by her fouling, practically sailing home on her barnacles.

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[7] Cast-iron was used in preference to zinc because it was cheaper and more easily procured. Davy cites several successful applications of protectors in which the proportion of the protecting metal varied from 1/70 to 1/125. Differing with Davy's statement, Hay says that the Navy Board ordered protectors of 1/80 of the copper surface.

[8] Although iron and steel were known in the 10th century B. C., iron was not used for ships' plates much before 1800, nor steel before 1865.

[9] As late as 1864, at the Institute of Naval Architects, Admiral Halsted described the flagship, undergoing an engine test at Sheerness, as shaking and trembling so that the master shipwright ran out, shouting, "For God's sake stop those engines as you'll drive the stern posts out of the ship."

Although fouling was by no means a new problem, its importance was so emphasized by the greater speeds, and by the substitution of costly and bulky fuel for sails, that many have felt that fouling became an important problem only with the introduction of iron ships. A man-of-war on commission in foreign waters for an extended period might become so fouled as to be almost unmanageable and unseaworthy before she came home and could be cleaned. The most extreme example reported was an iron whaler on the African coast, only six months out from England. Even though she had been cleaned every month with brooms and ropes, she was not safe, as she could neither sail nor steer, owing to her heavy fouling. So great did the problem become that in 1847 the Admiralty contemplated the total disuse of iron ships and actually commenced the sale of all the iron ships then in the Navy. They were deterred, however, by the impossibility of meeting naval requirements with any other material.

As a consequence of having invalidated the use of copper sheathing for an antifouling surface, the adoption of the iron hull started search for some less harmful metallic sheathing, and for some way of insulating copper sheathing from the iron hull.

Zinc, the only metal that could be used to place the plates of the ship in an electronegative condition, was tried repeatedly as sheathing. It was claimed that when in contact with the iron hull of a ship, electrolysis increased the exfoliation of the zinc sufficiently to prevent fouling, and at the same time protected the ships' plates from corrosion. Although zinc sheathing achieved some standing as a substitute for copper, experience showed that it sometimes became brittle and wasted away too fast to be of real value.

Muntz metal, sheet lead, galvanized iron, and nickel were tried, as well as alloys of lead and antimony, and of zinc and tin. Other metals or metallic alloys were suggested, and combinations of metals, such as iron scales covered with lead and copper, sheets of lead and antimony painted with mercury, or zinc plates coated with tin. Many of these sheathings presumably never passed beyond the experimental stage.

Nonmetallic sheathings were also tried or suggested. These surfaces included felt, canvas, and rubber; ebonite, cork, and paper. They also included various forms of glass, enamels, glazes, and tiles. Cement was frequently used, but more as a protection against corrosion than for fouling.

For insulating copper sheathing from the iron hull of the ship, felt soaked in tar was often used; and sometimes cork, rubber, or plain brown paper. At one time, warships were built in a composite fashion, i.e., wooden planks were put on iron frames. While various other considerations led to this development, the practice was favored also because such ships could be coppered safely. About 1862, this sytem was replaced by wooden sheathing put on over the metal hull. This was wedged between ridges on the hull, or bolted on in various ways, and then coppered. The wooden sheathing served only as an insulation. Although it was reported to have been satisfactory during the Spanish-American war (1898–99), and was used in both the British and the United States Navies, this method was too expensive for general use.

A second and more important effect of the introduction of iron hulls, however, was to renew interest in the use of antifouling compositions. This eventually led to the development of the modern paint systems which have replaced copper sheathing almost entirely, except when special needs warrant the extra expense.

Antifouling Paints

The use of some form of paint or composition on ships' bottoms is undoubtedly very old. An early record tells of a mixture in use about 412 B. C. composed of arsenic and sulfur, mixed with China oil, and applied to a ship's sides so that she could sail through the water "freely and without empediment."

Many other examples could be noted, from the tar and wax of ancient Greek boats to the various compositions used on the wooden sheathing of the 18th century.

Although some were said to be for protection against shipworms, in most cases the purpose of these various compositions was not stated. The first coating recorded explicitly as a protection against fouling appears to be a composition patented by William Beale in 1625, which was composed of powdered iron, cement, and probably a copper compound. Possibly, this was the first use of copper as an antifoulant.[10] Two other patents for unknown compositions for "gravings against the worm" were also granted in the 17th century; and a third was granted in 1670 to Howard and Watson for a coating composed of tar and resin in a varnish of beeswax, crude turpentine, and granulated lac dissolved in grain alcohol.

Three more patents were granted in the following century. One was for a composition containing pounded glass in a mixture of tar, oil, and lime; and a second for molten tin in a paste of zinc, limewater, black soap, and salts of zinc. The third, granted to William Murdock in 1791, was for a composition of iron sulfide and zinc roasted in air and mixed with varnish. Arsenic was the toxic.

But even though these early patented compositions were few and scattered, other unpatented compositions are also occasionally mentioned in the literature; and the use of some form of paint or composition on ships' bottoms was not uncommon.

Nicoalaes Witsen, a naval architect, wrote of the surprise of the Dutch that a British yacht captured in 1673 was neither tarred nor painted, which was apparently most unusual. Masseille states that fishermen on the Sea of Tiberius near Palestine are said to have used a mixture of crude turpentine, resin, suet, and asphalt in the 17th century. He also tells of a "coat hardening under water composed of suet, resin, fish-oil, and sometimes chalk," that was used on the French coast in the 18th century and that is still occasionally employed.

Several compositions were tested comparatively at Portsmouth in 1737. The best of these, a mixture of pitch, tar, and brimstone, was successful enough against ship worms to come into general use, but it was felt that it was highly important to find some surface that would also prevent fouling. Complaints were still being made of ship worms, however, particularly in the West Indies. This was represented to the Admiralty in a letter from the Navy Board in 1761, and in the same letter it was proposed to experiment with copper sheathing on some vessel going to the West Indies. The experiment on H.M.S. *Alarm* followed immediately. Two years later, the report on this experiment established the antifouling qualities of copper sheathing as so outstanding that for the next forty years there was only negligible interest in antifouling paints or compositions.

With the growing use of iron ships in the 19th century, attempts were made at first to adopt the new methods of sheathing so as to overcome the difficulties introduced by corrosion of galvanic origin. But by 1835 the futility of these efforts began to be recognized and attention was again turned to shipbottom paints.

From that time on, the number of paints and compositions increased rapidly. According to Young, by 1865 more than 300 patents for antifouling compositions had been issued in England alone.

The early patented compositions, for the most part, were entirely useless. Their ingredients included every useable material, organic and inorganic, from guano to plain kitchen salt. Owing to the great need for protection against fouling, however, many of even the most worthless of them were tried in service; although, as Admiral Sir Edward Belcher said, they seemed designed rather to encourage fouling than to discourage it. The Admiral added that his sailors got ten shillings each for the magnificently oversize specimens of shellfish that the various antifouling paints and manures succeeded in growing on the *Ardent* at Bermuda.

Antifouling paints had a bad reputation for many years. Even as late as 1872, Robert Mallet, in presenting the Institute of Naval Architects with a catalog of British shipbottom patents, stated that the majority of them were useless or worse, and that the best were mere palliatives. This was due in part to widespread lack of understanding of the problem, but not entirely so. Mallet himself, in 1841, had patented an antifouling paint in which slightly soluble coatings of poisonous materials were applied over a coat of varnish.[11] He stated that the paint failed because he could not control the solution rate of the toxics within useful limits, and because of abrasion.

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[10] The copper compound was possibly chalcocite or copper sulfide, or a copper-arsenic ore. Andes and Massaille, however, state that this ingredient was an unknown mineral from England or Wales.

"McIness," the first practical composition to come into widespread general use, was introduced in Liverpool about 1860. It was a metallic soap composition applied hot, in which copper sulfate was the toxic. This antifouling paint was put on over a quick-drying priming paint of rosin varnish and iron oxide pigment. Soon after this, a similar hot plastic composition appeared in Trieste, Italy. Known as "Italian Moravian," it was one of the best antifouling paints of that time and, in spite of being both expensive and difficult to apply, was used well into the present century.

In 1863, Tarr and Wonson patented a successful copper paint, a composition of copper oxide in tar, with naphtha or benzene; and later Rahtjen's equally successful shellac type paint, using mercuric oxide and arsenic as the toxics, was introduced. The use of shellac as a rust-preventive coating for ships' bottoms reduced the corrosion of ships to such an extent that in 1861 Admiral Halsted stated that corrosion was no longer important.

Owing in part to the commercial value of a successful antifouling paint, nearly all were patented, and our knowledge of them is derived largely from various patent records.

According to these records, the most frequently used toxics were copper, arsenic, and mercury together with their various compounds. They were used both singly and in combination with each other. Often several different compounds of the same toxic would be used in a single composition. Solvents included turpentine, naphtha, and benzene. Linseed oil, shellac, tar, and various resin or shellac varnishes composed the matrix.

By the end of the century, the most widely used paints were the hot plastics such as Moravian and McIness, the shellac type paints such as Rahtjen, and the various copper paints such as Tarr and Wonson's copper oxide in tar with naphtha or benzene. These paints were generally applied over a first or anticorrosive coat of shellac or varnish, or of the same composition without the toxic. Most naval vessels were using copper over a wood sheathing, or hot plastic compositions on their ships' bottoms. Other ships used the less expensive commercial paints; and wooden ships were still frequently sheathed with copper. These antifouling surfaces, however, although reasonably successful, were expensive, often short-lived, and occasionally uncertain; and fouling was still a major problem.

The commercial shipbottom paints used by the United States Navy prior to 1908 were purchased by competitive bidding; and there were no technical specifications and no inspections other than checking the quantity of paint delivered. In an effort to standardize the quality of the ingredients as well as for various practical considerations,[12] the Navy decided to manufacture its own antifouling coatings; and in 1906, experiments were begun on both shellac and hot plastic shipbottom paints.

The first tests of its own experimental paints were begun in June, 1906, at the Norfolk Navy Yard on 21 different shipbottom paint formulations of spirit varnish paints. By October of the following year, these tests indicated that one formula was outstanding. Further tests were made on naval bottoms at various Navy Yards with paints made from this formula, comparing it with commercial shipbottom paints; and on June 8, 1908, a report was made favorable to the Norfolk test paints. Not long after, manufacture of the first naval shipbottom paints was started at Norfolk Navy Yard.[13]

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[11] For toxics, Mallet used oxychloride of copper and sulfuret of arsenic.

[12] Among the practical considerations were the necessity of maintaining complete stocks of all the various brands of paint used at each of the Navy Yards, and the difficulties caused by the efforts of the competing paint manufacturers to get their paints accepted by the Navy.

The formula of an early Norfolk antifouling paint, as given by Adamson, shows that the toxic was red mercuric oxide suspended in grade A gum shellac, grain alcohol, turpentine, and pine tar oil. Zinc oxide, zinc dust, and Indian red were also added. Although the formula was continually varied, the shellac type paint was used by the Navy from 1908 until 1926, when it was abandoned.

From 1911 to 1921 further experiments were conducted at Norfolk, both to find substitutes for scarce materials and to improve the paint. In 1911, gum shellac of an excellent grade could be obtained from India, although the supply was limited. As wider use developed, it became both expensive and difficult to get. Inferior grades lacked adhesion, and experiments with various possible substitutes were carried on. Among these, rosin was of particular interest, both because of its successful use by some foreign navies and because of the cheap and plentiful supply in this country. A substitute was also sought for the toxic, mercuric oxide, which in addition to being expensive and of foreign origin was difficult to handle.

In 1921, the American Society for Testing Materials had formed a subcommittee on antifouling paints, with the object, if possible, of setting standard specifications for the toxic ingredients. They found, however, that factors other than the toxic were almost equally important; and an extensive investigation of the entire problem of fouling was begun in September, 1922, under the direction of the Bureau of Construction and Repair, U. S. Navy. At this time, most foreign navies were reported to be using commercial paints such as Holzapfel, Rahtjen, and Hempel; and the average effectiveness of the shellac type antifouling paints was said to be about nine months.

At the same time, the U. S. Navy renewed experiments with hot plastic paints. In the beginning of the century, the consensus of opinion had been that the Italian Moravian hot plastic was the best antifouling paint available. Analyses of commercial paints of this type had been made at the Brooklyn Navy Yard in 1906, and ways of producing them worked out; but with the official acceptance of the Norfolk shellac type paint in 1908, work on hot plastics had been dropped.

In 1922, at the request of the Navy Department, experiments in hot plastic antifouling paints were begun again by the Chemical Warfare Service at the Edgewood Arsenal. Various hot plastic compositions, based on analyses made at Edgewood in 1922, were made up and tested on steel panels at the Beaufort, N. C., station of the Bureau of Fisheries during the next two years. As a result of these tests, the Navy Department sent representatives from the Edgewood Arsenal to supervise a test application on the U.S.S. *King*, at the Norfolk Navy Yard. After nearly a year's cruising, the ship was docked at Mare Island on April 10, 1925; and it was reported that although the antifouling qualities had been excellent in the panel tests, the paint was not as successful in actual service. The film adherence, however, was good and further experiments were planned.

About 1926, the Navy substituted a coal tar-rosin formulation for the shellac type antifouling paint. Although coal-tar-rosin paints were used by the Navy until comparatively recently, the Mare Island Navy Yard, interested by the experiment on the U.S.S. *King*, had also developed a hot plastic shipbottom paint which used cuprous oxide and mercuric oxide as the toxics. Repeated tests have proved the Mare Island hot plastic superior to other available coatings. Extensive experience during the early years of the war has confirmed this superiority, and the hot plastic formula is currently the preferred paint for naval use on steel bottoms.

Hot plastic paints are troublesome because they require elaborate apparatus for application. Since the availability of such apparatus is limited, a need is still felt for superior antifouling coatings which may be applied by brush. This need led to the development of several satisfactory formulations known as cold plastics, which dry by evaporation of the solvent yet produce heavy films having much of the virtue of the hot plastic coatings.

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[13] Convincing proof of the value of the Norfolk formula, as compared to commercial paints, came from a service test on the ships of the U. S. Fleet on its cruise around the world in 1907.

Research and Development

The earliest published works concerned with the prevention of fouling of which we are aware are the papers of Sir Humphry Davy which appeared in the *Philosophical Transactions* of the Royal Society of London in 1824. Doubtless many reports of practical tests, such as that on the *Alarm*, and the tests of bottom compositions made at Portsmouth in 1737, existed in naval archives prior to this date. Davy's studies are noteworthy, however, because he made experiments, based on the best scientific knowledge of the time, to develop the principles controlling the fouling and corrosion of copper sheathing, and only then tested the methods which these experiments suggested on ships in service.

No man of Davy's scientific stature has since concerned himself with the fouling problem, and for more than three-quarters of a century no one approached the problem from the scientific angle followed by Davy. It is interesting to note in passing that a generation later another great English scientist, Charles Darwin, became the authority on barnacles and thus contributed valuable knowledge of the subject without apparently becoming concerned with its practical aspects.

The development of antifouling compositions during the 19th century appears to have been strictly empirical. The publications of this period consist of general discussions based on the experience of practical men: naval officers, naval architects, and shipbuilders. There was some speculation on how fouling is prevented, but never any controlled experiment designed to test principles or theories. The paints themselves were developed privately as proprietary products. How much systematic investigation underlay the patented or secret formulations is not recorded.

When paint research was first undertaken by the Navy, in 1906, the data available consisted largely of records of submersion tests which compared one commerical paint with another. Very little was known about the formulae. In starting tests, it was necessary to try many combinations of ingredients, and through a process of substitutions, eliminations, and alterations finally to arrive at formulae which would produce satisfactory paints. Some additional information was obtained by analyzing paints of commercial origin which showed promise, but because of the nature of paint ingredients the knowledge to be gained in this way was limited. Performance on panel test and in service remained the only guide to performance, and no means of judging the cause of failure was at hand.

The trial and error method of research gradually led to formulations which became more and more complicated, since each component which was introduced into a promising formulation tended to be carried along into subsequent modifications. In 1939 this tendency was reversed by an experiment conducted jointly by the Mare Island Navy Yard and W. F. Whedon of the Scripps Oceanographic Institution at La Jolla, in which the currently accepted hot plastic formulation was broken down into a series of simplified mixtures of its components. The object was to determine which ingredients were really essential. The outcome was the demonstration that the mercury and Paris green present in the original formula added nothing to its antifouling characteristics.

Prompted by a desire to obtain more fundamental knowledge of how to prevent fouling, the Navy arranged, from time to time, for biological investigations. This work supplied valuable information on the toxicity of potential paint ingredients to marine organisms, on the nature of the fouling population, its rate of growth, its seasonal and geographical incidence, and the relation of the service in which ships are employed to their tendency to foul. Similar studies were also conducted in Germany at the Laboratorium für Bewuchsforschung in Cuxhaven, in Turkey, Russia, and Japan, and in England.

The proposal that slimes, produced by bacteria and diatoms on submerged surfaces, had an important bearing on subsequent fouling aroused much interest and led to investigations which culminated in the establishment of the Naval Biological Laboratory at San Diego, and also initiated work at the Woods Hole Oceanographic Institution.

While this earlier biological work provided useful background knowledge that was requisite to intelligent attack on the problem, the idea that it would produce some unthought-of method of circumventing fouling proved illusory. However, the study of slimes led indirectly to two important results. First, the variability in the tendency of various paint surfaces to slime, and an apparent relation between slime formation and fouling, focused attention on the question of what property of the paint is responsible for its antifouling action. Second, experiments which were made to study the tendency of slimes to accumulate copper led to the development of techniques for measuring the rate at which copper or other toxics are given off by the paint surface. These methods, in turn, appear to have provided the answer to the above mentioned question: the antifouling action of currently successful shipbottom paints depends upon the rate of solution of the toxic material.

Armed with a definite physical objective, the problem of formulating antifouling coatings can now proceed in a more rational manner. What needs to be discovered is how to formulate so as to control correctly the discharge of toxic from the paint surface. The problem becomes one of applied physical chemistry rather than a game of permutations and combinations. Like Sir Humphry Davy, the paint technician can make experiments, based on the best available scientific information, to develop and employ the principles controlling fouling.

Contribution No. 615

The Commonwealth of Massachusetts

DEPARTMENT OF CONSERVATION
Arthur T. Lyman, Commissioner
DIVISION OF MARINE FISHERIES
Francis W. Sargent, Director

FOURTH REPORT ON

INVESTIGATIONS OF THE SHELLFISHERIES OF MASSACHUSETTS

Prepared by the
WOODS HOLE OCEANOGRAPHIC INSTITUTION
In Accordance with Contract
Effective July 1, 1951

PREFACE

The following report, prepared by Harry J. Turner, Jr., Biologist of the Woods Hole Oceanographic Institution, is a summary of the investigations of methods of improving the shellfish resources of Massachusetts which were carried out in 1951 by the Woods Hole Oceanographic Institution under contract with the Division of Marine Fisheries, Massachusetts Department of Conservation.

The investigations were conducted under the leadership of Mr. Turner. Those participating were J. Arthur Posgay, and David B. Sawyer, graduate assistants, and Robert Burden, summer assistant. The work was greatly aided by counsel from Dr. David L. Belding, former Biologist for the Massachusetts Department of Fisheries and Game who is now a member of the staff of the Woods Hole Oceanographic Institution.

The Institution has worked in close cooperation with the U. S. Fish and Wildlife Service which is conducting investigations in Essex County and in other parts of New England under a federal appropriation for the improvement of the soft and hard clam fisheries. Members of the Institution served on the Committee of Clam Technicians sponsored by the Atlantic States Marine Fisheries Commission of which Massachusetts is a member.

The Woods Hole Oceanographic Institution wishes to express its appreciation to Mr. Francis W. Sargent, Director of the Division of Marine Fisheries, and to Mr. Charles L. Wheeler, Biologist of the Division for their valuable suggestions and close cooperation.

Alfred C. Redfield
Associate Director
Woods Hole Oceanographic Institution

December 31
1951

FOURTH REPORT ON INVESTIGATIONS OF THE SHELLFISHERIES OF MASSACHUSETTS *

BY

HARRY J. TURNER, JR.

INTRODUCTION

During the past year the biological investigations of the Woods Hole Oceanographic Institution have further extended previous knowledge of the commercially important shellfish of Massachusetts. Emphasis has been shifted from experimental attempts at soft clam farming in depleted areas to the examination of existing populations of soft clams such as in Boston Harbor. Investigations of the feeding habits and growth rates of the boring snail, *Polynices*, have been continued, and additional data on the extent of migrations of the horseshoe crab, *Limulus*, have been acquired. Studies of the growth rate of the sea scallop have been carried on and plans for population estimates with an improved underwater camera have been formulated. Plans have also been made for experimental shellfish culture in the salt water ponds that can be excavated in marshlands.

Experimental clam farming was terminated at Barnstable Harbor, since a three year study had demonstrated that predators were too abundant to permit its financial success. The same conclusion was also arrived at by the biologists of the U. S. Fish and Wildlife Service, who had had similar experiences in other parts of Massachusetts and in Maine. Therefore, in order to determine what differences might exist between depleted and producing areas, it was considered advisable to examine populations of soft clams in Boston Harbor where clams were still found in commercial quantities. Analyses of the soft clam populations were made over approximately one fourth of the shoreline of Boston Harbor. Also the records of production during the past 20 years of the Division of Marine Fisheries were analyzed to determine trends in abundance.

Experimental work was continued on the enemies of the soft clam. A study of the boring snail, *Polynices*, revealed the average values of the food intake and the relative destructive capacity of snails of various sizes. The early life history of the harbor species, *Polynices duplicata*, was determined and it was possible to show how this species maintains a high level of abundance even during an acute shortage of soft clams. Additional returns of horseshoe crabs that were tagged and liberated in Barnstable Harbor during 1949 and 1950 increased our knowledge of the extent of their migrations, and tagging in 1951 in Wellfleet Harbor gave further evidence of the magnitude of the adult horseshoe crab population.

The determination of the extent and density of sea scallop populations in the important deep sea scallop fishery presented a difficult problem. Assays with standard dredges and a single-shot underwater camera proved unsatisfactory. However, preliminary tests with an improved camera, which was equipped with a multiple electronic flash unit capable of making several consecutive exposures, gave promise of photographing large areas of scallop beds. Detailed operations with this camera were temporarily deferred pending the availability of ship time and suitable weather conditions.

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* Contribution No. 615 Woods Hole Oceanographic Institution

During the past year a considerable number of inquiries were received concerning the possibility of utilizing artificial ponds for the culture of soft clams and other shellfish. These inquiries came from owners, or potential owners of marsh lands, who were considering excavating ponds for the purpose of growing shellfish as provided for in Section 28 of Chapter 130 of the General Laws Relating to Marine Fish and Fisheries. The prospective pond owners had in mind the possibility of controlling water masses to retain larvae, of fertilizing to increase the food supply, and of utilizing all the other advantages of private ownership. No encouragement was given because of the uncertainty of success and the necessity of a large initial investment. However, it was decided that experimental work along this line would be of value and plans were made to acquire a suitable locality.

THE SOFT SHELL CLAM FISHERY IN BARNSTABLE HARBOR

At the present time the soft-shell clam fishery in Barnstable Harbor is practically nonexistent. In 1947, when the exeperimental work was started on this harbor, there were only a few acres of soft clams that had been planted by the town, and a relatively small number of large wild clams scattered over a considerable area. Digging was intense and the predator population was high. Within two years the wild clams were so reduced in numbers by digging that the little remaining industry was entirely dependent on the planted beds. According to the shellfish officers the town plantings had been giving progressively smaller annual returns for some time, and within the last few years even these beds became depopulated before they were opened for digging.

Three types of experiments were originally conducted in Barnstable Harbor. (1) Barren areas were resurfaced with various materials to determine if certain types of soils would stimulate setting. (2) Soft clams were transplanted by various methods on barren flats that had been treated in different ways to determine the best methods of transplantation. (3) Barrier fences were erected to determine the possibility of excluding predators.

The resurfacing program for inducing clam sets was conducted for three years. Several one-sixteenth acre plots and subsequently two one-quarter acre plots were set out. The latter plots were resurfaced with materials that had the best lasting qualities. During the first year encouraging results were obtained, but it soon became apparent that the surface alterations, because of their roughness, concentrated young migratory clams rather than caught the direct set, and that the success was entirely dependent on generalized setting in the surrounding areas. The failure of such generalized sets to appear in the last two years prevented the appearance of young clams in the resurfaced areas.

Experiments in transplanting adult clams during the past four summers confirmed the conclusions of the earlier workers that soft clams could be successfully transplanted by broadcasting them on untreated flats without the additional labor and expense of plowing or otherwise preparing the surface. In this connection, the digging mechanism of soft clams was studied in aquaria by means of time-lapse movie photography, and it was found that small clams under two inches would begin to burrow after a quiescent period of a few minutes to several hours, but, when once started, the clams could bury themselves in from 10 to 15 minutes.

The importance of predators soon became apparent. Plantings made during the summer of 1947 were completely destroyed by the following spring with evidence pointing to the horseshoe crab as the responsible agent. Observations on the swimming and climbing habits of these animals showed that it was feasible to exclude them by fencing. Experiments proved that wire fences two feet high would exclude about 90% of the horseshoe crabs, if the bottoms of the fences were submerged a few inches below the surface of the sand. Soft clams in beds thus enclosed gave a somewhat better yield for a period of from 3 to 10 months than did those kept in unfenced beds. However, three other species of predators that were not excluded proved to be so destructive that the total yields even in the fenced plots were less than those of the original plantings. These other predators were boring snails that could pass through the fences, and green crabs and spider crabs that could climb or swim over the fences.

The poor yields of the planted beds, and the failure to devise practical methods of protecting them from predators led to the conclusion that clam culture in Barnstable Harbor would be unprofitable until natural forces intervened to reduce the predator populations or to provide sufficient wild molluscan food to divert them from commercial plantings. This situation is not unique to Barnstable Harbor, but is present according to federal and state investigators in other parts of Massachusetts and Maine.

THE HORSESHOE CRAB AND THE SOFT CLAM FISHERY

The destructive capacity of the American horseshoe crab for soft shelled clams has been recognized for years by clam diggers and biologists. It is customary in some localities for clam diggers and shellfish wardens to destroy all the horseshoe crabs that they can find on clam flats. The annual records which are kept by some towns show that horseshoe crabs first appear in May on Cape Cod and that their numbers increase to a peak in about the third week in June. Thereafter, their incidence declines so that by the end of August only a few specimens can be found even after a lengthy search. Persons who are employed to kill horseshoe crabs are usually encouraged by finding a declining number of crabs after the month of June, and naturally conclude that their efforts are actually causing this reduction.

A recent study of the natural history and habits of the horseshoe crab in Barnstable Harbor by Shuster demonstrated that the progressive decrease in numbers of the horseshoe crabs during the middle and late summer resulted from their seaward migration rather than from the reduction of the population Tagging experiments showed that the population of adult horseshoe crabs was much too large to be appreciably affected by the numbers reported as killed, and also that the crabs in Barnstable Harbor were part of a population inhabiting a considerable portion of Cape Cod Bay. Several hundred horseshoe crabs

Chart of Barnstable Harbor

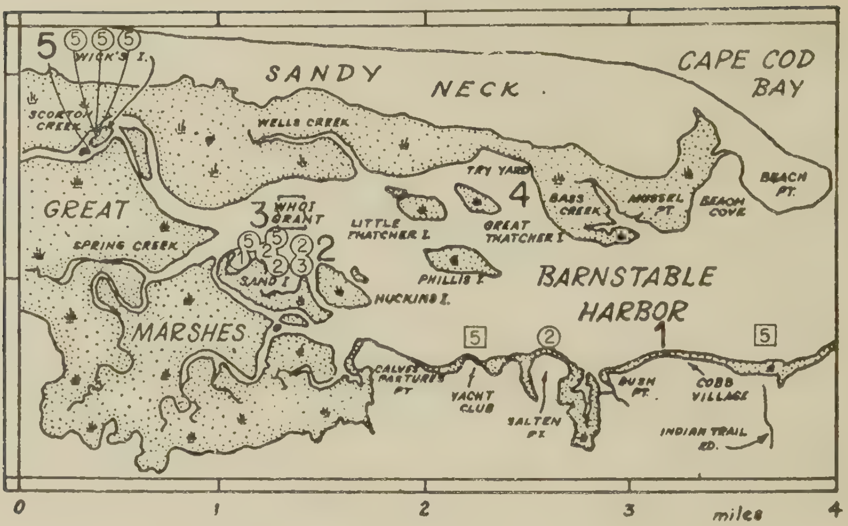
SANDY NECK
CAPE COD BAY
GREAT MARSHES
BARNSTABLE HARBOR
WICK'S I.
SCORTON CREEK
WELLS CREEK
SPRING CREEK
WHO'S GRANT
LITTLE THATCHER I.
GREAT THATCHER I.
TRY YARD
BASS CREEK
MUSSEL PT.
BEACH COVE
BEACH PT.
SAND I.
PHILLIS I.
HUCKINS I.
CALVES PASTURE PT.
YACHT CLUB
SALTEN PT.
BUSH PT.
COBB VILLAGE
INDIAN TRAIL RD.
0
1
2
3
4
miles

Chart of Cape Cod Bay

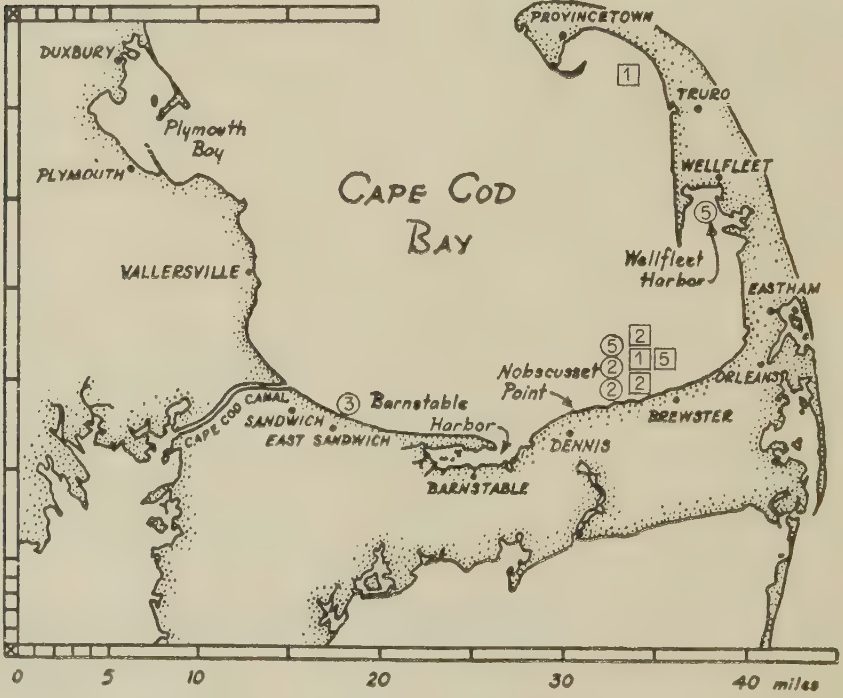
CAPE COD BAY
DUXBURY
Plymouth Bay
PLYMOUTH
VALLERSVILLE
CAPE COD CANAL
SANDWICH
EAST SANDWICH
Barnstable Harbor
BARNSTABLE
DENNIS
Nobscusset Point
BREWSTER
ORLEANS
EASTHAM
Wellfleet Harbor
WELLFLEET
TRURO
PROVINCETOWN
0
5
10
20
30
40 miles

Figure 1.

Summary of the 1950 horseshoe crab tagging experiments. Plain numbers indicate places where tagged horseshoe crabs were released during the summer of 1950. Circles indicate recaptures during 1950. Squares indicate recaptures during 1951. Numbers in the circles and squares indicate the location where the crabs were originally released.

tagged with plastic discs inscribed with directions for their return were liberated during the summers of 1949 and 1950 in Barnstable Harbor. The 1949 tagging experiment produced two returns from outside the harbor, one from the outer beach on Sandy Neck during the same summer, and one from Dennis Beach the following year. The program was intensified during the summer of 1950; tagged animals being released at different times and in different parts of the harbor. The results are summarized in Figure 1. Most of the recaptures were made within a few days near points of release, but later, tagged individuals began to appear on the beaches of Cape Cod Bay, even as far as North Truro 20 miles away.

The general eastward migration that is suggested in Figure 1 may be erroneous because the success of tagging marine animals for which there is no commercial fishery depends upon the accidental finding of specimens by bathers and picnickers. Thus it may be valid to assume that as many crabs came ashore along the inaccessible beaches to the westward of Barnstable Harbor as appeared on the more frequented beaches of Dennis, Wellfleet, and Truro. However, these tagging experiments do definitely establish the interchange of horseshoe crabs between Barnstable Harbor and Cape Cod Bay. This fact, along with estimates of the vast size of the Cape Cod Bay horseshoe crab population, indicates the futility of attempting to reduce the supply of these crabs by killing a few hundred in any one locality.

A similar experiment was concluded in Wellfleet in the spring of 1951 to determine whether or not the horseshoe crabs of that locality formed a local population. At the mouth of Blackfish Creek over 200 crabs were marked with brightly colored poultry rings, a technique satisfactory for following local migrations. No marked crabs were found in subsequent visits to the same locality, or elsewhere within the harbor, although the children of the town had been informed of the experiment and promised a small reward for returns. In the fall a dead marked crab was found on the Cape Cod Bay shore, five miles north of the entrance of the harbor. Apparently the horseshoe crabs in Wellfleet Harbor are both numerous and migratory, and any local efforts to reduce their numbers would be as futile as in Barnstable Harbor.

These conclusions have been confirmed in Plum Island Sound by biologists of the U.S. Fish and Wildlife Service. The horseshoe crabs in that locality probably belong to a separate population from those of Cape Cod Bay, as is indicated by the smaller size of the adults. Here marking experiments suggest a very large general population with lengthy migrations in the region north of Cape Ann.

THE SURVIVAL OF THE BORING SNAIL ON DEPLETED CLAM FLATS

The destructive propensities of the boring snail, *polynices duplicata,* have been recognized for some time by biologists and clammers. The results of the previously mentioned planting experiments have clearly shown that boring snails may be so abundant even on flats where there are no clams, that transplanted beds, acting as baited areas, attract them in large numbers. It is well known that carnivores, particularly fur-bearing mammals, decrease in numbers with a decline of their food supply. Thus it is somewhat of a puzzle how such large populations of snails can continue to survive in the apparent absence of food, since this snail is carnivorous and cannot subsist on the algal ooze or detritus.

Investigations initiated by Sawyer in 1950 and continued through 1951 have shown that there is a secondary food supply that can sustain a population of considerable size for a limited period during the early life of the young. The tiny duck clam, *Gemma,* a small quahaug-like mollusk, seldom more than one quarter of an inch in length, occurs in enormous numbers on many of the flats of Massachusetts. The snails lay their numerous eggs encased in characteristic sand collars in June and July. Hatching occurs in about two weeks and the larvae emerge as tiny snails equipped with swimming organs. They become widely dispersed during this free swimming stage and after an undetermined time settle to the bottom as crawling snails. After settling to the bottom they apparently feed chiefly on *Gemma,* as well as on other available small mollusks. Growth is so rapid that few snails smaller than 8 mm across the opercular opening are ever found. At this stage, their food requirements are prodigious; about one-third their own weight in clam meat per week is necessary to just sustain life and the small snails will eat as much as one-sixth more, an excess which is used for growth. By the time their opercular opening reaches a length of 10 to 12 mm, the snails either refuse to eat *Gemma* or are unable to eat enough to provide for growth. As a result many small snails whose growth has been restricted by starvation may be found on barren flats at all times of the year. A few which are fortunate enough to find small razor clams or mussels may get enough food in a single feeding to cause a rapid increase in size. Such individuals then have a decided advantage over their less fortunate relatives, since their increased size enables them to attack mature razor clams, quahaugs, and other large mollusks. These individuals can then grow normally and ultimately form the breeding stock.

This vast reservoir of undernourished individuals is an important antagonistic factor in the development of our soft clam resources. The introduction of local concentrations of soft clams on a barren flat either as the result of setting or transplantation will attract large numbers of these starving snails. The increased food supply then permits rapid growth of the snails with a correspondingly increasing destruction of the clams. An example of this phenomenon was observed in the planting experiments during the summer of 1950. Soft clams were planted in a 25-foot square that was enclosed by a chicken wire fence, the mesh of which excluded all snails whose opercular openings were over 15 mm long. The snail population in the vicinity contained mostly individuals whose opercular openings averaged 9 mm in length. When the clams were dug after a period of three months, 195 snails were found, all with opercular openings measuring 20 mm or more. The quantity of clam meats consumed, calculated from the bored shells that were recovered, was found to correspond with the estimated amount required to increase the size of the snails from the average size in the surrounding starved population to that found in the clam beds.

It is thus apparent that the continuation of the populations of the boring snail and its high destructive potential is the result of a series of complex interrelationships between the biology of the snail and its varied sources of food. The free swimming stage permits wide dispersal so that destruction of egg masses in any limited locality does not preclude repopulation. The presence of *Gemma,* although an inefficient source of food, permits survival of the young, and provides a bare subsistence for a population of semi-starved snails, ready to prey on soft clams or other mollusks when they become available.

SHELLFISH CULTURE IN SALT WATER PONDS

During the past year there have been several requests for information relative to the possibility of raising shellfish in salt water ponds. Several individuals have been of the opinion that the practically valueless salt marshes of the Massachusetts coast could be developed by excavation into private shellfish growing areas under control of the owner. Section 28 of Chapter 130 of the General Laws Relating to Marine Fish and Fisheries provides the legal measure that establishes private ownership of such areas. The situation is comparable to the development of fresh water fish ponds in the inland farming districts, where suitable control has produced crops of fish with an acreage yield in considerable excess of natural bodies of water.

It is impossible to predict the success of such a venture at the present time since there is available no experimental data nor past experience. There are, however, certain biological and economic principles that can be analyzed from a theoretical point of view so as to indicate whether or not pond culture is feasible.

The first consideration is the theoretical productive potential of a salt water pond. It is obvious that a salt water pond represents a capital investment of considerable magnitude and that it requires funds for maintenance. Thus the shellfish produced in this pond would cost the owner a certain amount even before they are harvested, and it would be necessary that the quantity and density of the shellfish be so great that the expense of harvesting would be less than that of digging wild shellfish, which cost the digger only the value of his equipment and the time expended in digging. Thus, from a practical point of view, the shellfish should grow in sufficient abundance that the cost of harvesting would be considerably below that of digging wild shellfish. It is necessary, therefore, to determine whether or not a salt water pond has a theoretical productive potential to make the operation economically feasible.

There are records of natural beds of soft clams containing a standing crop of 1,000 bushels per acre, with a meat equivalent of 15,000 pounds. Such concentrations have been the accumulation of 3 to 5 years growth giving a minimum yearly production of 3,000 pounds. It would be necessary that production in salt water ponds be sustained at something like this magnitude, and theoretical considerations from comparisons with fresh pond fish culture suggest that it would be possible. Fresh water fish ponds can produce 300 pounds of fish per acre annually if properly managed. With few exceptions the fish raised are carnivorous and live on invertebrate animals. Most organisms consume 10 or more times their own weight in food before reaching maturity so that fresh water fish ponds must produce 3,000 pounds of invertebrate food per acre per year. If a simple direct food chain is developed, the invertebrate animals feed on microscopic plants which are the primary and limiting source of the pond's production. The yearly production per acre of pond must be 10 times the weight of the invertebrate animals or 30,000 pounds. Thus, a fresh water pond supporting a fish population that can be harvested at the rate of 300 pounds per acre per year must grow microscopic algae at the rate of at least 30,000 pounds per acre per year. Losses from various sources coupled with additional stages in the food chain may make it necessary to increase this figure many times.

The possibility of producing shellfish at a rate 10 times that at which fresh water fishes are grown is based on the assumption that the soft clams, quahaugs, and oysters feed on plant plankton, or the organic detritus derived from it. The intermediate links in the food chain are thus eliminated so that a one-acre pond producing 3,000 pounds of clam meats per year would have to produce 30,000 pounds of miscroscopic plants. This is equivalent to the figure derived for fresh water fish ponds. The productive capacity of marine waters is ample to maintain this figure, since Riley has determined that the average yearly production per acre is 3.2 tons (6,400 lbs.) of dry plankton or over 100,000 pounds of wet plankton. Therefore, it would seem that the theoretical productive capacity of salt water ponds could be sufficient to grow shellfish at a rate that would be commercially profitable.

There are other factors of a practical nature, however, that must be taken into consideration. A pond excavated in a marsh adjacent to marine waters must have some degree of connection with the sea or bay to maintain adequate salinity and to renew nutrient elements. The greater the degree of such an interconnection, the less would be the possibility of controlling the environment. Even if techniques are evolved for maintaining a completely separate body of water under satisfactory conditions, there are other complicating factors. Theoretically, a satisfactory *quantity* of food for shellfish can easily be produced, but there is some question as to whether the quality would be such that the shellfish could or would utilize it. It has been recently shown that certain miscroscopic algae or their metabolic products inhibit the feeding of oysters, and certain bays where these organisms now occur in vast numbers have lost their ability to grow oysters. At the present time, unfortunately, there is a lack of knowledge concerning the exact food requirements and preferences of the commercial mollusks. Thus it is impossible to predict how any species will react to a random assortment of miscroscopic algae in an enclosure where one or more species may become the predominant type.

In the final analysis, the use of artificial salt water ponds for shellfish culture is theoretically possible. The potential productivity of plant food for the shellfish is more than enough to provide rapid growth in heavy densities. The practical aspects depend on the testing of certain assumptions and the working out of associated mechanical problems.

THE SOFT CLAM FISHERY OF BOSTON HARBOR

Boston Harbor is the chief area in Massachusetts now producing soft-shell clams in commercial quantities. Its waters are more or less contaminated with domestic sewage from the thickly populated metropolitan district so that special regulations apply both to the taking and marketing of soft clams. These regulations have made it possible to follow statistically the local production of clams over a period of years in a way that would be impossible for any other clamming area in Massachusetts. The regulations may be summarized as follows:

Soft clams from moderately contaminated areas may only be taken by holders of a master digger's permit or their employees. The clams are transported to the purification plant at Newburyport where they are decontaminated with chlorinated water before marketing. The master digger makes a report to the Division of Marine Fisheries that includes information as to the number of diggers, the quantity of clams dug, and the areas from which they were taken. Records are also kept at the purification plant so that there is a cross check on each master digger's report.

It is impossible to obtain such detailed information for other soft clam fisheries in Massachusetts. Commercial digging in uncontaminated localities is carried out under a mass of local regulations that vary from town to town, and the clams are sold in a variety of ways without passing through a central agent. The situation is further complicated by digging for home consumption, for recreation, and for bait. Thus, in most localities the condition of the soft clam fishery is completely obscured until the abundance of clams falls so low that the fishery practically ceases to exist. By that time it is too late to determine the causal events leading to the decline, because of the lack of statistical records.

Boston Harbor was selected as the one remaining locality from which valuable information on the soft clam fishery could be obtained, first, because reliable records covering a period of years of exploitation were available and, second, because a high proportion of the soft clams produced in Massachusetts during the last few years was dug in this area. The trend of the fishery was calculated from records supplied by the Massachusetts Division of Marine Fisheries from which the quantity of clams per digger per day could be estimated. The actual populations of soft clams were studied in the field by sampling selected areas and by determining the assorted sizes of clams found in measured areas of flat. Ages were estimated from growth lines on the shells so that some idea of the rate of growth could be determined. The great length of the perimeter of the harbor and the limitations of time, tides, and weather made it impossible to cover more than a quarter of the clam producing areas during the past year.

DESCRIPTION OF THE AREA

Boston Harbor is a major indentation of the Massachusetts coast line that resembles a semicircle with a five mile radius. The seaward (east) side of the harbor is protected by two points of land, Deer Island on the north side and Nantasket (Hull) on the south. Four necks extend eastward from the perimeter of the harbor, dividing it into five distinct bays, each a sector of the semicircle. Numerous islands are scattered about the harbor in such a way as to separate further the bays. The beach profiles are relatively steep between the tide lines, with a leveling off at the low tide mark. On neap and ordinary tides clamming is restricted to the steep beaches while spring tides expose broad level flats, many of which are covered with mussels.

Hingham Bay, which was investigated during the summer and fall of 1951, is the southernmost bay in Boston Harbor. It has the longest coast line of all the bays and contains the greatest area free from pollution. Hingham Harbor, Weir River, and the inner shore of the town of Hull contain extensive clean flats while the moderately contaminated borders of Weymouth Fore River and Weymouth Back River are dug by master diggers and their employees. There are also limited areas around several islands where clams may be taken for decontamination.

The steeper beaches are rocky or pebbly with the clams between the rocks and pebbles. The digging of these clams necessitates the use of hoes larger and sturdier than are commonly used. The lower flats and heads of indentations are generally paved with gray or black soil at times so soft that a person walking sinks in ankle deep. Here the standard Ipswich digger or flat tined south shore hoe may be used. In many places the inroads of mussel beds have ruined potential clam areas.

HISTORY OF THE SOFT CLAM INDUSTRY

There were no restrictions on the digging of soft clams in Boston Harbor prior to 1906. In that year the Massachusetts State Board of Health determined that there was considerable danger of a spread of enteric disease by clams taken from areas contaminated with domestic sewage, and requested the Department of Fisheries and Game, the law enforcement agency, to close all of Boston Harbor except Hingham Bay. The closed area included about three quarters of the harbor and caused considerable hardship to the local clam diggers. The situation was somewhat alleviated by the granting of permits to take limited quantities of clams for bait, for which there was a considerable demand at that time by the commercial fishing fleets. The restrictions were relatively severe and generally limited the permittee to one or two bushels daily, or at most four bushels in any two successive days. Early records show that about 180 persons took advantage of bait permits in 1907, many of whom probably used the clams for their own sport or commercial fishing because some of the permits limited the quantity to as little as one peck per day.

The early records give no information as to the probable production of Boston Harbor, and newspaper articles indicate that such information, even if it existed, would probably be unreliable. Regulation of clam digging in Boston Harbor proved most difficult to enforce. Newspaper accounts indicate that the few clammers arrested for digging without permits or selling bait clams for food were shown considerable leniency by the courts.

The situation remained in this unsatisfactory condition until about 1920. There were occasional editorial outbursts in the newspapers, some demanding resurveys of the harbor and others calling for stricter law enforcement. There was an increasing appreciation of the danger to the public health and more and more of the harbor was found to be contaminated. By 1920 so much of the harbor was closed to digging and law enforcement was improved to such a degree that the soft clam industry of Boston Harbor became practically nonexistent.

In 1926, the Lawrence Experiment Station of the Massachusetts Department of Public Health began a series of experiments to determine the relationship between the densities of human intestinal bacteria in shellfish and in the sea water of their immediate environment. A substantial agreement between the two was found so that it soon became possible to classify waters into categories signifying the probable degree of pollution to be expected in the clams living in these habitats. At the same time preliminary experiments indicated that soft clams from areas of moderate contamination could be satisfactorily purified if they were held for a short time in sea water containing a low concentration of chlorine. More elaborate experiments in 1927 provided the basic information that made possible the practical purification of clams on a commercial scale. In 1928 construction of a purification plant at Newburyport on Plum Island was started and plans were drawn up for similar plants at Scituate and Plymouth. All three plants were ready for operation by 1931 and restrictions were relaxed to permit digging under supervision in polluted areas. For practical purposes this date marks the beginning of the modern soft clam industry in Boston Harbor. The purification plant at Plum Island is still in operation and now handles shellfish from all the contaminated areas of the Commonwealth. No deliveries were made to the plant at Plymouth after 1936, and the Scituate plant ceased operations in 1940. In recent years there has been a considerable amount of interest in the building of a new plant, and money has been appropriated by the General Court for that purpose. Construction, however, has been delayed because no satisfactory location has as yet been found.

PRESENT REGULATION OF THE FISHERY IN CONTAMINATED AREAS

The danger of diversion of contaminated shellfish into the commercial food channels without purification has made necessary the enactment of controlling legislation. At the present time the law provides that the Director of the Division of Marine Fisheries may issue three types of permits for the digging of soft clams from contaminated areas. A master digger's permit is issued to persons who dig and/or employ others to dig clams for subsequent purification. Employees of master diggers must hold diggers' permits. Bait permits are also issued, but holders of permits for digging shellfish to be purified for human consumption are ineligible for bait permits.

The responsibility for the successful operation of this fishery rests with the master digger. He is in effect the manager of the resources. He hires the diggers, determines where they shall dig, buys their product, and transports it to the purification plant. Intelligent master diggers usually manage their operations from a long term point of view. They may direct their diggers to certain flats on extra low tides, reserving other more available ones for short tides. They may limit digging in newly set areas to prevent destruction of seed clams. Many master diggers insist that their diggers leave a certain number of clams in the flat in order to prevent complete depletion. Others operate on a rotational scheme, leaving certain flats untouched for long periods so that repopulation and growth may occur. Thus the exploitation of contaminated shellfish areas is carried out much more systematically than is done in the uncontaminated areas. The regulations limiting the industry to persons who are willing to apply for permits prevent careless exploitation by casual diggers, tourists, etc., and preserve the soft clam resources for those who earn their livelihood by clamming.

TREND OF CLAM ABUNDANCE IN BOSTON HARBOR

The condition of a fishery resource may be indicated by the trend in abundance of the species over a considerable period of time. Rising trends indicate that the species is not being exploited to its fullest extent, while falling trends indicate that greater numbers are being removed by both fishing and natural mortality than are being produced by repopulation and growth. Under ideal conditions, abundance should be maintained at a constant level, a condition which is unattainable in nature, since fluctuations in repopulation, growth, and death rates often occur as a result of causes too complex for analysis.

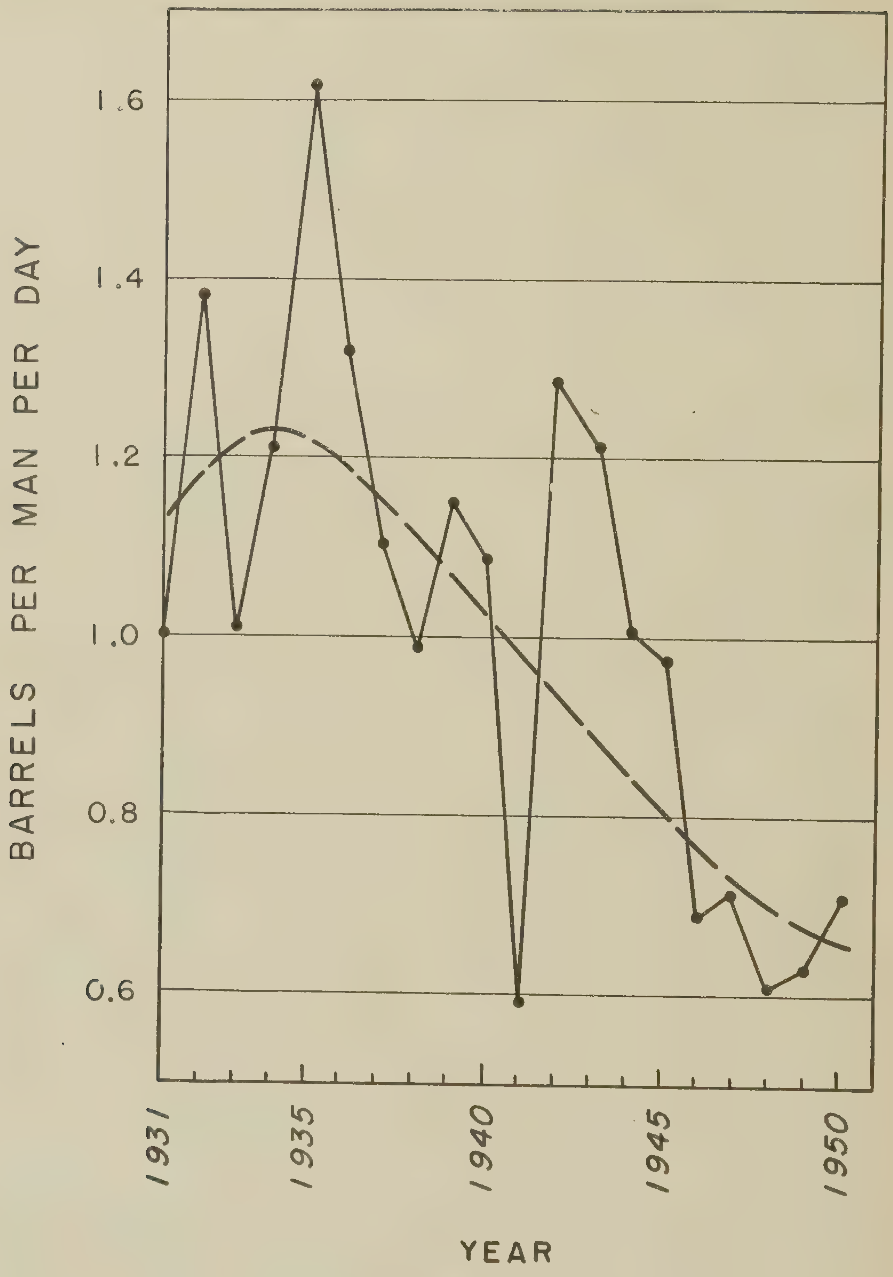

Figure 2.

Graph of the index of abundance of soft clams in Boston Harbor from 1931 through 1950. The solid line is the actual index calculated from digging statistics. The dashed line is an approximate average indicating the trend.

Abundance is usually estimated from the catch per unit of effort. It is assumed that a fisherman can catch more fish or dig more clams when they are abundant than when they are scarce and that the amount will be proportional to the abundance. It is generally believed that variations in skill, weather conditions and other similar factors average out when sufficient data are available. False indications sometimes occur when social or economic conditions bring about radical changes in the fishing personnel so as to introduce different levels of skill. Improvements in gear and methods also change indices of abundance, and provide high returns that are not necessarily valid.

The trend of abundance of soft clams within the confines of Boston Harbor is shown in graph, Figure 2. The plotted units represent barrels per man per day. The average trend indicated by the dashed line clearly shows that the abundance of soft clams in Boston Harbor has been declining. This fact can be even more clearly shown by simply comparing the average catch per man per day during the prewar years with that of the postwar period. The war period is purposely left out of the analysis because of the various changes in the digging personnel brought about by military service and war production demands. The average catch per man per day during the prewar period was 1.2 barrels as compared with 0.67 barrels during the postwar period. Thus the present abundance of soft clams in Boston Harbor is but slightly more than one half of the supply during the period between 1931 and 1940. Additional evidence of this decline is indicated by a change in the field of operations of the master diggers. The records show that previous to 1941 each master digger and his crew operated throughout the year in restricted localities within the harbor. In 1941, however, certain master diggers began to explore other areas adjacent to Boston Harbor such as the flats of Revere, Lynn, Saugus, Beverley and Danvers and this practice has continued up to the present time. This extension of the field of operations suggests that the master diggers, finding that the abundance of clams in their local areas was insufficient to satisfy their needs, enlarged the scope of their operations to include areas that had been previously untouched.

There is some question as to whether Boston Harbor is being overdug even though the average index of abundance has shown a downward trend. It is probable that the higher indices of abundance prevalent in the prewar years may have been due to accumulations of clams that took place while the harbor was closed to digging prior to 1931. If the present index of 0.67 barrels per man per day remains at a constant level for the next 10 years or more, it will indicate that the harbor is being dug to its full production capacity. This ideal condition will mean that the soft clam resources are being utilized efficiently. A continued downward trend, however, will indicate overdigging, with eventual collapse of the industry when the abundance of clams becomes so low that the natural mortality is greater than the rate of repopulation and growth.

THE SOFT CLAM RESOURCES OF HINGHAM BAY

Hingham Bay is bordered by the towns of Hull, Hingham, Weymouth,* and Quincy. Its irregular coastal features, comprising numerous headlands, coves, and inlets, provide a wide variety of tidal flats in which soft clams are present in varying abundance. The most extensive uncontaminated areas in Boston Harbor are found in the towns of Hingham and Hull, while the flats of Weymouth and Quincy are only moderately contaminated and produce clams that may be marketed after purification.

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* Not included in this report.

Hull - The uncontaminated area in the town of Hull includes a stretch of beach extending northward from Sunset Point for a distance of about two miles. The northern half of this beach, which has an intertidal zone about 200 feet wide, is stony and contains few clams. The southern half to the south of Strawberry Hill widens to about 300 feet, and continues to increase in width southerly until it terminates in a cove at the base of Sunset Point. Most of the digging is done in this cove which has an intertidal area of about 15 acres. The soil is stony so that digging is difficult and breakage is high. In June 1951 the average density of the clams on these flats was 11 per square foot, of which 4 or 5 exceeded the two-inch legal minimum length. The approximate quantity of marketable clams in the entire area was estimated to be somewhere between 1,000 and 3,000 bushels. The rate of growth was only moderate. The legal clams were about four years old, and most of the smaller ones three. The proportion of one and two-year-old clams was so low that apparently this area would become commercially unproductive in about two years unless a new set of clams materialized in the interim.

The narrow beach that extended northward from the cove at Sunset Point comprised a total area of about 10 acres, which contained scattered clams in insufficient numbers to permit an estimation of their abundance. Here the stony character of the soil made digging difficult. However, there was some evidence of digging, probably for home use by local residents or vacationists. It is doubtful that commercial diggers would exploit the area except as a last resort.

There are two moderately contaminated areas in Hull, one to the north and around Hog Island, and one south of Sunset Point. Both areas had apparently been dug over although neither was being dug at the time of examination. The northern area consists of a narrow stony beach with one small cove where the soil consisted chiefly of coarse sand and clay. This area of about seven acres contained an average of seven clams per square foot ranging from 1 to 2¼ inches in length. There were approximately 400 bushels of legal size clams in the area at the time of examination. The scarcity of small clams made it seem unlikely that the area will be productive for some time.

Future prospects appear better in the area south of Sunset Point, although the inroads of mussel beds have restricted the clamming area to a fraction of the entire beach. There are two promising sections: a five-acre sand spit situated halfway out on the southern edge of Sunset Point, and the cove at its base. In the former area the clams averaged 45 per square foot and showed a varied assortment of age groups. The majority, one year old, averaged about an inch in length. Age analyses of the larger specimens indicated that the legal size could be reached in 3 to 4 years. It is reasonable to expect that this flat may contain about 2,000 bushels of clams in 2 to 3 years if one half of the clams survive. The latter area, the head of the cove on the south side of the base of Sunset Point, comprises 12 acres of soft muddy sand. This area, which showed evidence of previous digging, contained about 25 clams per square foot, of which less than a fifth were over two inches in length. Over one half of the clams were two years old and averaged about an inch in length. The larger clams showed a slow rate of growth, indicating that it would require at least four and often five years for a clam to reach legal size in this cove. In spite of the slow growth, the preponderance of young stock forecasted good digging in about three years.

The total acreage of flats in the town of Hull containing appreciable quantities of soft clams is about 32. There are about 10 more acres of stony beach containing scattered clams in too small abundance to be of commercial importance. The 15 acres of uncontaminated beach had an appreciable standing crop of clams during the summer of 1951 but the future prospects were not bright. On the other hand there were 17 acres of moderately contaminated flats that contained a reserve of undersized clams that should mature in 2 to 3 years. A considerable area of potential clam flats has been made valueless by the encroachment of mussel beds.

Hingham - The soft clam areas of the town of Hingham consist of the Weir River, Hingham Harbor, and the Weymouth Back River shores. Part of the Weir River area and most of Hingham Harbor are free from sewage contamination. Approximately one third of the Weir River flats are moderately contaminated, and a small section comprising less than one tenth of Hingham Harbor is severely contaminated so that all digging is prohibited. The Weymouth Back River shores are all moderately contaminated. The aggregate uncontaminated flats of the town of Hingham comprise more than a square mile, most of which is exposed on ordinary low tides. The soil is generally rocky or stony near the shores, while farther out the flats usually are of soft mud. Mussel beds which have sprung up in several places are the source of some concern. The vast area and varying abundance of soft clams make it impossible to estimate the clamming potentialities. The town shellfish committee is active and makes use of the grossly contaminated area as a seed source for the rest of the harbor. The efficient shellfish constable rigidly enforces the regulations. On the whole, the situation appears quite favorable and the resources are in a healthy condition.

The shoreline extending from Hingham Harbor around Crow Point into Weymouth Back River is for the most part a gravel beach. It is included in the moderately contaminated category and has a limited intertidal zone. One or two small coves showed evidence of previous digging and contained clams in patches with densities of 5 to 10 per square foot, but they are too scattered to permit estimation of the clam population. Evidently these areas had been worked over by the master diggers' crews and are now undisturbed pending repopulation.

Quincy - The clam flats of the City of Quincy that are included in Hingham Bay occur in Town River, Rock Island Cove, and along Manet Beach. All are moderately contaminated and are only dug over by master diggers and their crews. Town River contains from 80 to 100 acres of soft mud flats. The area was dug over in 1950, when the density of clams was about 35 per square foot with about one-half of marketable size. Rock Island Cove and Manet Beach are contiguous and include approximately 150 acres of heavily dug clam flats. The soil in Rock Island Cove generally consists of fine sand with soft mud in the inlets and creeks at the head of the cove. The clams number about 20 per square foot, most of them just under two inches in length. Their irregular distribution makes an accurate estimate of the standing crops impossible.

Manet Beach runs north from Rocky Point which partially separates it from the flats of Rock Island Cove. The beach consists of sand and gravel, with a gentle downward slope for a distance of from 100 to 200 feet. At this point a firm sand beach levels off to extend several hundred feet to the low water mark. Commercial clamming is carried out in the gravel zone where clams, though numerous, are too irregularly distributed to permit an approximation of their abundance. This area is subject to more or less continuous digging. In this locality a very dense set of small clams was discovered in the fine sand of the lower beach in the vicinity of Raccoon Island. The set covered an area of about 15 acres, with one half of the area so densely populated that all the available surface was occupied by tiny clams. The set will be described in detail in another section of this report.

The soft clam resources of the City of Quincy that lie within Hingham Bay consist of from 230 to 250 acres of moderately contaminated area. The flats are readily accessible to the master diggers and their crews and consequently are heavily exploited. Digging is difficult either because of the softness of the substratum as in Town River Bay and Rock Island Cove, or due to the presence of gravel and stones along Manet Beach. The nature of the soil, which makes digging difficult, renders it impossible for the flats to be cleaned out completely. Thus clammers can practically always find some areas where the clam population is sufficient to make digging worthwhile.

The Islands - There are four islands in Hingham Bay that provide an auxiliary source of clams, when the supply in other areas becomes low. The beaches surrounding these islands are classified in the moderately contaminated category and thus are available only to master diggers and their employees. Three of the islands were examined during the summer of 1951. Bumpkin Island lies northwest of Sunset Point, Hull. Its northern side, which is exposed to considerable wave action, is narrow and stony and is unsuitable for the existence of soft clams. Scattered clams are found in the gravel, stones and mussel beds along the southern side, but their present number is too small for commercial clamming. Grape Island and Slate Island lie near the mouth of Weymouth Back River. Their northern borders are similar to that of Bumpkin Island. There are soft clams in sufficient abundance in scattered patches along the southern borders to interest the master diggers of Quincy. The legal clams number about five per square foot but they are situated at a rather shallow depth so that digging is relatively easy. At the time of examination in 1951 diggers from Quincy averaged about a barrel of clams per day on the southern shores of Grape Island.

The abundance of soft clams in the summer of 1951 in Hingham Bay appeared to have been affected to a considerable degree by the method of clamming to which the flats had been subjected. Practically all the moderately contaminated areas showed evidence of having been systematically worked over and then abandoned. This system followed by the master diggers appeared to have had a favorable effect, since it allowed full utilization of the adult clam stocks and permitted recovery without the disturbance of continuous digging, as was indicated by the relatively high abundance of small clams. The uncontaminated flats, on the other hand, were undergoing continuous unsystematic exploitation by individuals instead of by directed groups. Continuous production may be achieved in this manner but the constant disturbance of the substratum appeared to have had an adverse effect on the seed clams. Recent analyses by Canadian authorities on the effects of digging on the younger stocks have shown that the mortality in the younger clams is appreciable each time the ground is dug over. Therefore, it is reasonable to believe that continuous digging may have an even greater destructive effect. The evidence suggests that uncontaminated areas throughout the Commonwealth might benefit by a method of management involving systematic rotation of areas with closed seasons of sufficient duration to permit efficient recovery.

THE RACCOON ISLAND SET

A set of soft clams near Raccoon Island, Hough's Neck, Quincy provided an unusual opportunity to study the setting behavior of the soft-shell clam. This set deserves special mention, since it is the heaviest and most spectacular set ever recorded. Such sets have rarely been observed, and with the exception of a set on Rowley Reef, Plum Island Sound in 1907, and also in Barnstable Harbor in 1950, there have been no written records or extensive investigations of the few heavy sets that have been observed.

The set covered approximately 15 acres of low lying flat between Rocky Head and Raccoon Island, Quincy. Of this area, a section of seven acres contained small clams in densities ranging to over 10,000 per square foot. All the available surface of the flat was occupied by tiny clams that were forcing each other out of the sandy mud as growth increased crowding. Broken shells were numerous and clumps of seaweed that had been washed up by the waves were almost entirely covered with small clams that had attached themselves to the weeds by the byssus. Large numbers of clams were collected for experimentation by gathering the encrusted seaweed in boxes for transfer to Woods Hole.

On August 22, 1951 the clams averaged ⅜ of an inch in length with a total range of from ⅛ to ⅝ of an inch. Considerable numbers were planted in various coves and ponds in the Woods Hole region where the presence of adult clams indicated that the conditions were suitable for growth. The clams began to dig in and establish themselves within a few minutes after planting but within a week the clams began to die off in all areas, and were entirely gone within a month.

Selected large specimens averaging about one-half an inch in length were placed in a salt water aquarium with sand at the bottom. They buried themselves readily and appeared to feed in a normal manner. However, they began to die within a few days and none of them survived longer than three weeks.

When the original site was revisited in November, it was found that the density of the set and the area including it was considerably reduced. The density varied from 1,600 per square foot near the seaward border to 2,000 per square foot near the landward side. The most striking change was in the size of the clams. They were all smaller than the original ones that were present in the area in August, varying in length from one fifteenth of an inch (just visible) to one quarter of an inch. The beach was littered with tiny broken shells of the August set with huge accumulations in windrows at the upper levels and in the pockets left by diggers. Evidently there had been a steady mortality in clams of the larger sizes with continuous replacement with setting clams. The degree of mortality made it seem probable that only about one per cent could be expected to survive to the following spring.

There has always been considerable speculation as to the manner in which soft clams set. It has generally been thought that setting takes place within a short period of time as the result of a single mass spawning. The Raccoon Island set demonstrates clearly that setting can continue for a period of at least three months. This situation is probably the result of intermittent spawning of parent stocks in various parts of Boston Harbor, the variation in duration of the larval period, and the migratory habits of the larval and post-larval crawling-swimming stages.

The failure of survival in these massive clam sets presents an interesting problem. The death of the clams that were transplanted in the Woods Hole area could easily have resulted from exposure and handling during transportation rather than an inherent weakness in the young clams. However, no one has yet been able to demonstrate successful transplantation of very young clams owing either to their migratory tendencies, to the inroads of the enemies, or the inability to survive. In practically all the recorded massive sets of clams, the mortality has been extremely high. In this set the mortality was the highest ever recorded in spite of the survival and replacement of the stock. The actual numbers were such as to account for a large part of the loss because of space limitations. The effect of physical factors such as wind, tide, and currents affecting the surface of the flat, the contamination of the living by decomposing dead clams, and the possibility of epidemic disease may also have contributed to the destruction.

THE BIOLOGICAL EFFECTS OF CLAM DIGGING

Overdigging is frequently considered to be the primary cause of the present widespread scarcity of soft clams in the New England states. It is the one adverse factor in the ecology of the clam for which man is responsible, and which man also attempts to control by legislation. The direct effect of removal of clams does not seem to be sufficient to explain failures in propagation and excessive mortalities in undersized stocks, but there appears to be a complex series of indirect effects that influence the dynamics of soft clam populations as a whole.

The primary effect of digging is the removal of a large percentage of the clams over two inches in length and the destruction of a certain number of the smaller ones by breakage. This reduces, but does not eliminate, the spawning stock because soft clams become sexually mature long before reaching the two-inch length. It is not clear how this influences repopulation because of the nature of the reproductive process. Soft clams, like many other marine organisms, liberate millions of eggs and sperm, and provide no means of protection for the resulting larvae that drift helplessly in the water for a considerable period of time before setting. It is generally considered that successful propagation in such organisms is for the most part independent of the size of the parent stock because environmental conditions appear to be much more important in the survival of the larvae than the original numbers. It is not uncommon for a single large generation to originate from depleted parent stocks.

There is some reason to suspect that the removal of the larger members of the soft clam population may be beneficial. Growth rates have been shown to increase as population densities are decreased, and some investigators believe that clams that are disrupted by digging grow faster after reestablishing themselves. Likewise the thinning out of exceptionally dense populations provides space for successive generations to occupy after setting.

The size and composition of a population of soft clams may influence the mortality due to predation, and alterations in these qualities may intensify this effect. This can be demonstrated in a simple way with a hypothetical example. If a bed contains equal numbers of one and two-inch clams, there will be eight times as many bushels of the latter group as there are of the former. This is because clams increase their volume eight times whenever the length is doubled. A predator feeding at random in this bed will destroy equal numbers of clams in a given period, but eight-ninths of his food will be derived from the two-inch group. If all the two-inch clams are removed by digging, the predator will have to consume 8 one-inch clams for each two-inch clam that had previously been available. Thus it will take 9 one-inch clams to equal the volume provided by 1 two-inch, and 1 one-inch clam, so that the predator will be consuming numerically 4.5 times as many clams.

The exact influence of digging on the continued productivity of the soft clam probably varies so greatly from one locality to another that no generalizations can be made. In the final analysis, the cumulative effect of digging plus natural mortality determines the trend of abundance. When a greater quantity of clams is removed by both factors than is produced by reproduction and growth, the population declines.

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Contribution No. 616

ABRUPT CHANGE IN WIDTH IN TWO-LAYER OPEN CHANNEL FLOW[1]

BY

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ABSTRACT

An abrupt widening in a channel can act as a control on the regime of two-layer flow immediately upstream. A simple explanation in terms of an interfacial Froude number is offered and a set of experimental verifications is described. Bernoulli's Principle is applied to an abrupt narrowing.

1. *The Interfacial Froude Number.* The ordinary Froude number, F, is defined by

$$F = u^2/gD\ , \tag{1}$$

where u is the mean velocity of flow in a channel of depth D. A long wave of infinitesimal amplitude is stationary when $F = 1$, a condition which occurs in any channel transition which acts as a control.[2]

In a two layer system a transition may be expected to act as a control on the level of the interface when a long internal wave of infinitesimal amplitude is stationary.

For convenience we have defined the interfacial Froude number, F_i, in terms of u_1, the mean velocity of the upper layer, and D_1, the depth of the upper layer, and the quantity $\beta = (\rho_2 - \rho_1)/\rho_2$, where ρ_1 and ρ_2 are the densities of the upper and lower layers respectively:

$$F_i = u_1^2/g\beta D_1\ . \tag{2}$$

The condition for a stationary internal wave also depends on u_2, the velocity, and D_2, the depth of the lower layer; hence it is not generally as simple as $F_i = 1$. The steady state equations of motion for the two layers are

$$u_1 \frac{\partial u_1}{\partial x} = -g \frac{\partial}{\partial x} (D_1 + D_2) \tag{3}$$

and

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[2] "Engineering Hydraulics," edited by Hunter Rouse. John Wiley and Sons, New York. 1950.

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$$u_2 \frac{\partial u_2}{\partial x} = - g \left[\alpha \frac{\partial \, (D_1 + D_2)}{\partial x} + \beta \frac{\partial D_2}{\partial x} \right], \tag{4}$$

where $\alpha = \rho_1/\rho_2$ and $\beta = (\rho_2 - \rho_1)/\rho_2$.

The equations of mass continuity are

$$(\partial/\partial x)(D_1 u_1) = 0 \tag{5}$$

$$\text{and } (\partial/\partial x)\ (D_2 u_2) = 0 \, . \tag{6}$$

TABLE I. Critical Interfacial Froude Number F_i as a Function of n and q_2/q_1

n \ q_2/q_1		*.1*	*.2*	*.3*	*.4*	*.5*	*.6*	*.7*	*.8*	*.9*	*1.0*
0	1	1	1	1	1	1	1	1	1	1	1
.1	1	1	1	1	1	1	1	1	.999	.999	.999
.2	1	1	1	.999	.997	.996	.994	.992	.990	.987	.984
.3	1	.999	.993	.993	.987	.980	.973	.962	.951	.940	.927
.4	1	.997	.988	.974	.955	.931	.904	.873	.841	.807	.772
.5	1	.990	.962	.917	.862	.800	.735	.671	.610	.552	.500
.6	1	.967	.881	.767	.649	.543	.451	.377	.316	.268	.229
.7	1	.888	.665	.469	.332	.235	.181	.139	.110		
.8	1	.610	.281	.148							
.9	1	.121				Less than 0.1					
1.0											

Elimination of $\partial u_1/\partial x$, $\partial u_2/\partial x$, $\partial D_1/\partial x$, and $\partial D_2/\partial x$ from these four equations results in the following equation, which must hold for stationary interfacial waves:

$$G_2\ (G_1 - 1) = G_2 - \beta \, , \tag{7}$$

where we have written for simplicity $G_1 = u_1^2/gD_1$ and $G_2 = u_2^2/gD_2$.

Since the regular Froude number in two-layer flow is very small, $G_1 << 1$, we may write the following very good approximation of (7): $G_1 + G_2 = \beta$.

If we introduce the discharges per unit width, $q_1 = u_1 D_1$ and $q_2 = u_2 D_2$, and the quantity n by $D_1 = nD$, then $D_2 = (1 - n)\ D$, where D is the total depth. We write the interfacial Froude number for stationary interfacial waves in the following form:

$$F_i = \left[1 + \left(\frac{q_2}{q_1} \right)^2 \left(\frac{n}{1-n} \right)^3 \right]^{-1} .$$

Values of the critical F_i are given in Table I; for reasonably small values of both q_2/q_1 and n, F_i is essentially unity.

2. *Experimental Runs on Control.* The flume shown in Fig. 1 was fitted with a transition in width. The lower layer of liquid was in all cases sea water; the upper layer was fresh water or a mixture of fresh and salt water (to provide various densities). The different widths of the flume used before the transition were 4.0, 8.5, 17.5, and 27.0 cm. The width of the flume after the transition was in every case 44.0 cm. The nature of the flow past the transition is shown in Figs. 2 and 3. Table II contains the data from the series of experiments: W is the width before the transition, W_1 is that after the transition, D_1 is the depth of the upper layer measured upstream beyond the region of curvilinear flow. D_{1T} is the depth of the upper layer at the beginning of the transition. D_2 is the depth of the lower layer at the point where D_1 was measured. D_1^* is the depth of the upper layer computed from the assumption that $F_i = 1$. In most of the runs a slight counterflow in the lower layer was unavoidable due to some mixing across the interface. The velocity of flow in the lower layer was much less than that in the upper layer and exhibited a vertical distribution similar to that shown in Fig. 4.

Measurements of D_1 from photographs were made with a probable error of $\pm$ 0.3 cm. The standard deviation (all runs) of the observed depth of the upper layer, D_1, from computed depth D_1^* on the assumption that $F_i = 1$ is $\pm$ 0.56 cm.

3. *Application to Estuaries.* Certain estuaries realize the conditions of this type of control. The Mississippi River enters the Gulf of Mexico through a number of passes, two of which, South Pass and Southwest Pass, are artificially confined by jetties so that the transition in width is very abrupt.[3] The flow in both passes is distinctly two-layered at low river discharges, the interface is very sharply defined, and there is negligible tidal mixing. The depth of the upper layer, as observed and computed, is given in Table III.

For model studies it is inferred that if the model is scaled properly for surface tides (Froude scaling) the action of controls on the two-layer flow will also be properly scaled, provided the densities of the model and their differences are the same as those in the prototype. A change of density difference precludes the possibility of scaled control of interfacial depth.

4. *Abrupt Contraction.* When the channel transition does not act as a control, the flow in the upper layer can be conveniently analyzed with Bernoulli's Theorem. We will neglect the velocity of the lower

[3] Mr. H. B. Simmons and Mr. G. H. Hudson of the U. S. Army Corps of Engineers very kindly provided the authors with data on the hydrography of these Passes.

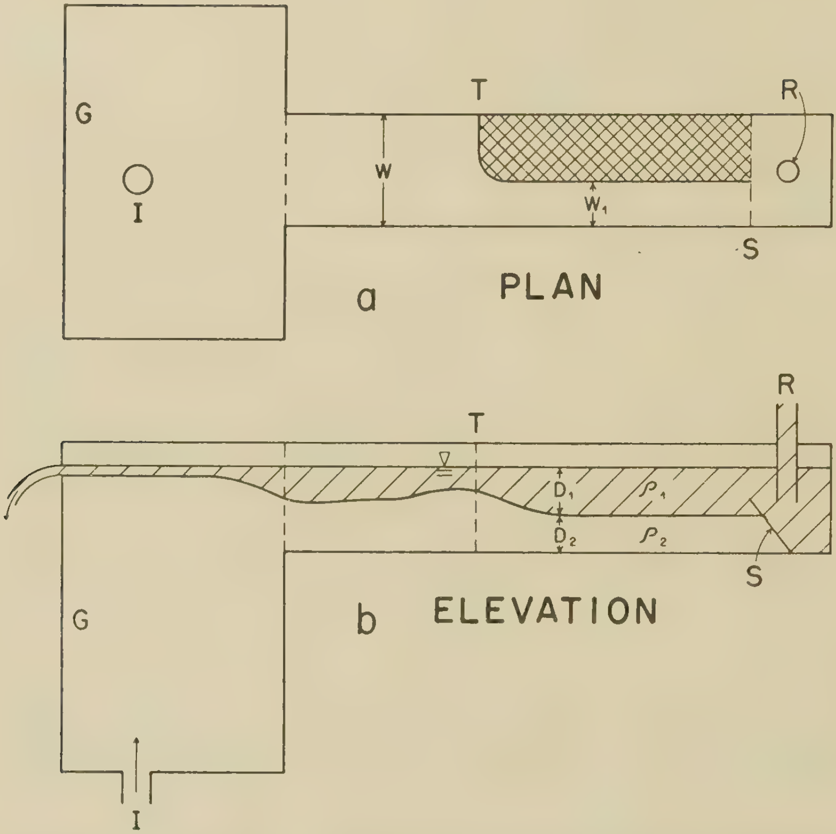

Figure 1. *a* and *b* show the plan and elevation of the set-up of the transition in the flume for an abrupt widening. The transition is at *T*, the river mixture enters at *R*, the separator, *S*, prevents mixing of the two layers at the river inlet, the heavy salt water is constantly replenished through inlet, *I*, at the bottom of the salt water tank. Both fluids flow out over the gate, *G*, which controls the free surface level. The upper fresh water layer is shaded. *c* and *d* (see opposite page) show the set-up for the abrupt narrowing of the flume. In all cases the edge of the transition is rounded with a three inch radius.

layer and assume that the velocity of the upper layer is uniform before and after the transition and that the pressure is everywhere hydrostatic. Using the same notation as before, the energy equation may be written as

$$\frac{\rho_1 u_1^2}{2} + (\rho_2 - \rho_1) gD_1 = \frac{\rho_1 u_1'^2}{2} + (\rho_2 - \rho_1) gD_1' + E .$$

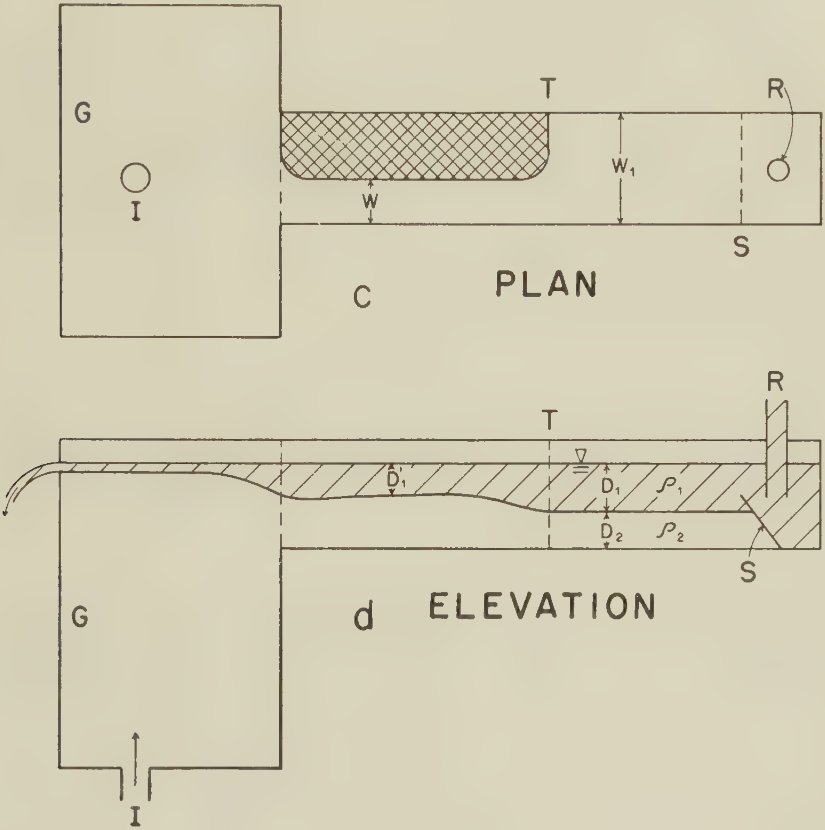

Figure 1 (*continued*)

The left-hand side of the equation refers to a section upstream of the transition, that on the right to a section downstream of the transition, both sections being beyond the region of curvilinear flow. E represents the energy loss or change in total energy before and after the transition. Table IV contains 24 runs made through a narrowing. Fig. 4 shows a typical run. The quantity $(D_1 - D_1')^*$ is computed on the assumption of $E = 0$. Comparison with the measured $(D_1 - D_1')$ shows agreement well within the errors of measurement, which demonstrates the minor role of the turbulent energy loss in a narrowing.

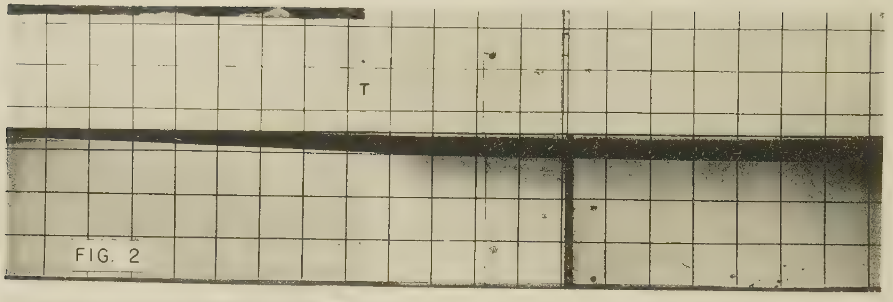

FIG. 2

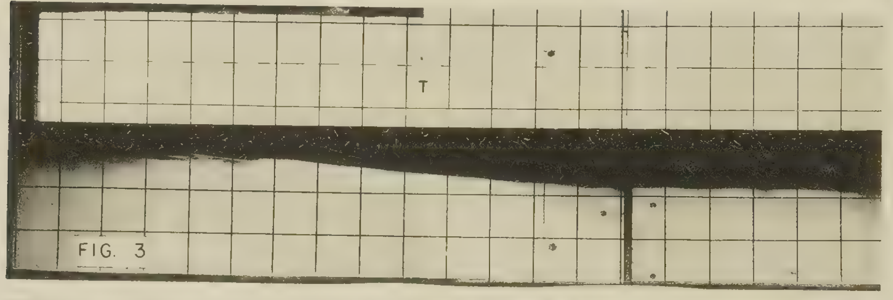

FIG. 3

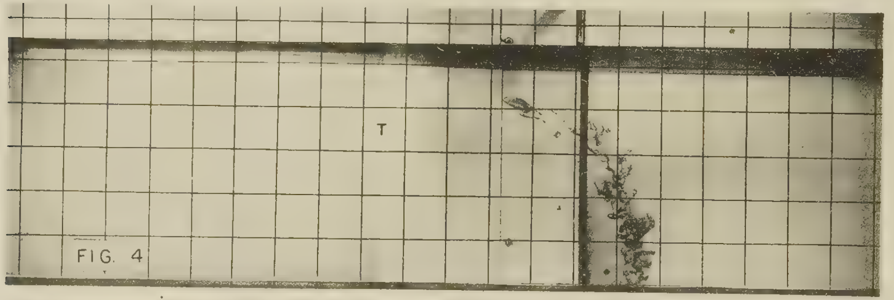

FIG. 4

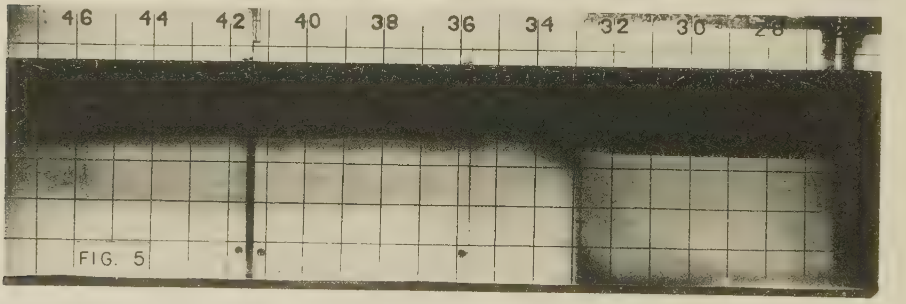

FIG. 5

Figures 2 and 3. Illustrative examples of flow past sudden widening at T, runs C-3-16 and C-3-18 respectively. View through glass side of flume. The grid lines are 5 cm apart. The lower 5 cm of the flume are obscured by the shade on the photographic lamps. The upper fluid, dyed black, moves from right to left. Figure 4. The distribution of dye 10 seconds after release from the heavy vertical black line to illustrate the slow creeping motion of the lower layer, run C-3-21. Figure 5. Bernoulli flow through abrupt narrowing, run E-3-6.

TABLE II

Run	$\beta \times 10^3$	q_1	D_1	D_2	D_{1T}	D_1^*
			$W_1/W = 0.091$			
C-3-127	8.09	31.5	6.2	26.3	4.5	5.0
128	18.6	94.5	7.2	25.3	5.2	7.9
129	9.56	63.0	8.7	23.8	6.5	7.5
130	8.78	94.5	10.7	21.8	7.5	10.1
131	7.60	189.	15.5	17.0	11.5	16.8
132	8.10	31.5	5.8	16.7	4.1	5.0
133	9.07	94.5	10.0	12.5	7.2	10.0
134	9.56	31.5	5.7	6.8	3.8	4.7
135	21.9	31.5	4.5	8.0	3.0	3.6
136	24.3	31.5	4.0	18.5	3.0	3.5
137	21.4	94.5	8.5	14.0	5.5	7.5
138	23.8	189.	11.5	11.0	8.2	11.5
			$W_1/W = 0.19$			
C-3- 1	21.1	14.8	3.0	10.0	2.2	2.2
2	2.34	44.5	4.3	8.7	3.0	4.4
3	23.2	89.0	6.8	6.2	4.8	7.0
4	22.3	14.8	2.8	19.7	2.2	2.2
5	21.6	44.5	4.5	18.0	3.4	4.5
6	24.1	89.0	7.0	15.5	5.1	6.9
7	24.4	178.	10.5	12.0	8.0	11.0
8	23.6	14.8	2.8	29.7	2.2	2.1
9	19.5	44.5	5.0	27.5	3.5	4.7
10	22.6	89.0	7.5	25.0	5.4	7.1
11	24.4	178.	11.0	21.5	8.5	11.0
69	16.5	14.8	2.8	9.7	2.0	2.4
70	16.6	44.5	4.6	7.9	3.5	5.0
71	15.1	89.0	7.5	5.0	5.5	8.1
72	13.1	14.8	3.2	19.3	2.3	2.6
73	14.4	44.5	5.5	17.0	4.1	5.2
74	15.4	89.0	7.5	15.0	6.2	8.0
75	16.4	178.	12.4	10.1	9.0	12.5
76	13.7	14.8	3.2	29.3	2.5	2.5
77	15.0	44.5	5.6	26.9	4.0	5.1
78	14.8	89.0	8.0	24.5	6.0	8.2
79	15.8	178.	11.5	21.0	9.0	12.7
81	8.20	14.8	4.1	28.4	2.9	3.0
82	10.3	44.5	6.6	25.9	5.0	5.8
83	8.77	89.0	9.5	23.0	7.0	9.7
84	7.90	178.	14.7	17.8	11.1	16.0
85	8.20	268.	20.0	12.5	14.5	20.7
86	7.90	14.8	4.0	18.5	2.7	3.0
87	10.0	44.5	6.0	16.5	4.5	5.9
88	9.26	89.0	9.2	13.3	7.0	9.6

TABLE II *(Continued)*

Run	$\beta \times 10^3$	q_1	D_1	D_2	D_{1T}	D_1^*
$W_1/W = 0.19$ *(Continued)*						
C-3- 89	7.90	178.	15.0	7.5	11.0	16.0
90	8.10	14.8	3.4	9.1	2.5	3.0
91	11.6	44.5	6.0	6.5	4.7	5.6
92	6.05	14.8	4.0	18.5	3.1	3.3
93	8.10	44.5	6.2	16.3	4.5	6.3
94	8.00	89.0	9.0	13.5	6.9	10.0
95	7.90	178.	15.1	7.4	11.0	16.0
96	7.12	14.8	4.5	28.0	3.5	3.2
97	9.75	44.5	6.0	26.5	4.5	5.9
98	10.2	89.0	9.1	23.4	7.3	9.3
99	8.00	178.	14.5	18.0	11.5	15.9
100	8.00	268.	20.0	12.5	15.0	20.9
$W_1/W = 0.40$						
C-3- 12	23.0	21.6	2.8	9.7	2.7	2.8
13	23.6	43.2	4.5	8.0	3.5	4.3
14	24.1	86.4	7.0	5.5	5.6	6.8
15	19.6	7.2	2.0	20.5	1.5	1.4
16	22.0	21.6	3.0	19.5	2.5	2.8
17	22.8	43.2	4.5	18.0	3.6	4.4
18	23.6	86.4	6.7	15.8	5.9	6.8
19	24.0	130.	9.0	13.5	7.7	9.0
20	23.0	7.2	2.0	30.5	1.5	1.3
21	20.7	21.6	2.7	29.8	2.4	2.8
22	21.9	43.2	4.7	27.8	3.9	4.4
23	23.3	86.4	7.0	25.5	5.9	6.9
24	23.6	130.	9.2	23.3	8.0	9.0
53	14.9	21.6	3.3	9.2	2.5	3.2
54	15.5	43.2	5.0	7.5	4.0	5.0
55	16.1	86.4	7.8	4.7	6.3	7.8
56	15.2	21.6	3.5	19.0	2.6	3.2
57	15.4	43.2	5.7	16.8	4.0	5.0
58	16.0	86.4	7.6	14.9	6.2	7.8
59	15.9	130.	10.4	12.1	8.5	10.2
60	16.2	172.	12.2	10.3	10.0	12.3
61	15.0	21.6	3.4	29.1	2.7	3.2
62	16.0	43.2	5.1	27.4	3.6	4.9
63	16.1	86.4	7.7	24.8	6.4	7.8
64	16.0	130.	9.8	22.7	8.0	10.2
65	16.2	172.	12.5	20.0	10.0	12.3
66	11.7	7.2	2.5	30.0	1.8	1.7
67	14.6	7.2	1.9	20.6	1.4	1.5
68	16.4	7.2	2.1	10.4	1.5	1.5
101	6.60	7.2	2.2	30.3	2.2	2.0

TABLE II (*Continued*)

Run	$\beta \times 10^3$	q_1	D_1	D_2	D_{1T}	D_1^*
$W_1/W = 0.40$ (*Continued*)						
C–3–102	8.68	21.6	4.0	28.5	3.6	3.8
103	8.66	43.2	6.3	26.2	5.2	6.0
104	7.31	130.	13.5	9.0	11.0	13.3
105	7.70	172.	17.0	5.5	12.5	15.8
106	6.34	7.2	2.5	20.0	2.0	2.0
107	9.17	21.6	4.0	18.5	3.3	3.7
108	7.80	43.2	6.5	16.0	5.0	6.3
109	7.20	86.4	10.7	11.8	8.5	10.2
110	7.31	130.	13.5	9.0	11.0	13.3
111	7.70	7.2	2.2	10.3	1.9	1.9
112	8.78	21.6	4.2	8.3	3.5	3.8
113	7.70	43.2	6.5	6.0	5.0	6.3
$W_1/W = 0.61$						
C–3– 25	20.8	4.67	1.5	11.0	1.1	1.0
26	20.8	14.0	2.8	9.7	2.2	2.1
27	24.0	28.0	3.9	8.6	3.2	3.2
28	24.1	55.9	6.0	6.5	4.5	5.1
29	24.2	84.0	7.0	5.5	6.0	6.7
30	19.4	4.67	1.4	21.1	1.3	1.0
31	21.8	14.0	2.0	20.5	1.6	2.1
32	23.0	28.0	3.2	19.3	2.7	3.3
33	23.8	55.9	5.0	17.5	4.5	5.1
34	24.0	84.0	7.2	15.3	6.4	6.7
35	23.3	4.67	1.5	31.0	1.1	1.0
36	21.3	14.0	2.0	30.5	1.8	2.1
37	21.8	28.0	3.1	29.4	2.8	3.3
38	23.2	55.9	5.0	27.5	4.5	5.2
39	23.7	84.0	7.1	25.4	6.0	6.7
41	15.7	28.0	3.7	8.8	3.1	3.7
42	16.2	55.9	5.5	7.0	4.6	5.8
43	16.2	84.0	7.5	5.0	6.5	7.6
44	15.0	14.0	3.0	19.5	2.0	2.4
45	14.9	28.0	4.0	18.5	3.5	3.8
46	15.8	55.9	6.2	16.3	5.2	5.9
47	16.3	84.0	8.0	14.5	7.0	7.6
48	14.7	14.0	2.6	29.9	2.4	2.4
49	14.8	28.0	3.7	28.8	3.0	3.8
50	16.0	55.9	6.0	26.5	5.2	5.8
51	16.0	84.0	8.0	24.5	7.1	7.7
52	16.0	112.	10.5	22.0	8.6	9.3
114	7.50	14.0	3.4	9.1	2.5	3.0
115	8.20	28.0	5.0	7.5	4.0	4.6
116	7.00	55.9	8.5	4.0	6.7	7.7

TABLE II (*Continued*)

$W_1/W = 0.61$ (*Continued*)

Run	$\beta = 10^3$	q_1	D_1	D_2	D_{1T}	D_1^*
C-3-117	6.40	4.67	2.0	20.5	1.6	1.5
118	7.10	14.0	3.4	19.1	2.7	3.0
119	8.10	28.0	4.5	18.0	3.5	4.6
120	7.10	55.9	8.2	14.3	6.5	7.7
121	7.50	112.	12.0	10.5	9.0	11.9
122	7.10	4.67	2.0	30.5	1.4	1.5
123	7.00	14.0	3.5	29.0	2.8	3.1
124	7.80	28.0	5.2	27.3	4.0	4.7
125	7.00	55.9	7.9	24.6	6.2	7.7
126	7.40	112.	13.0	19.5	11.5	12.0

TABLE III

Case number	1	2	3	4
River discharge ft³ sec⁻¹	3×10^4	6×10^4	10×10^4	20×10^4
q_1 ft²/sec	20	40	66	134
D_1 measured ft.	12	15	20	31
D_1 computed ft.	11	17	23	35

TABLE IV

Run	$\beta \times 10^3$	q_1'	D_1	D_2	$D_1 - D_1'$	$(D_1 - D_1')^*$
			$W_1/W = 5.1$			
E-3- 1	18.7	14.5	4.2	19.0	0.6	0.5
2	22.9	72.5	9.0	14.0	1.1	1.7
3	24.0	145.	15.5	8.0	2.5	2.5
4	20.8	14.5	5.0	27.5	0.7	0.3
5	20.5	43.5	7.9	25.0	1.5	1.1
6	22.8	87.0	11.2	22.0	1.7	1.7
7	23.5	174.	17.9	16.0	2.9	2.8
8	22.9	14.5	4.5	8.5	0.6	0.3
9	23.5	43.5	6.5	7.0	1.0	1.2
10	23.8	87.0	11.0	2.0	1.2	1.5
11	14.7	14.5	4.7	8.0	0.7	0.5
12	15.8	43.5	8.7	4.0	1.3	1.1
13	13.9	14.5	4.7	18.0	0.5	0.4
14	14.1	43.5	9.0	14.0	1.5	1.2
15	6.73	14.5	6.0	7.0	1.0	0.7
16	23.5	43.5	8.0	5.0	1.0	0.8
17	8.10	43.5	10.7	12.5	1.6	1.4
18	6.83	87.0	16.2	6.5	2.2	2.7
19	7.71	43.5	10.0	23.0	1.3	1.5
20	7.12	87.0	15.5	17.0	2.0	2.7
21	6.44	174.	27.5	6.0	4.5	4.5
			$W_1/W = 9.8$			
E-3-22	7.12	84.0	18.1	15.0	2.1	3.1
23	7.12	168.	27.0	6.0	4.0	3.8
24	7.02	42.0	11.0	21.5	1.5	1.4

Contribution No. 619

THE SURFACE LAYER OF THE GULF STREAM AND ADJACENT WATERS[1]

By

WILLIAM L. FORD AND A. R. MILLER

ABSTRACT

This paper presents a description of the Gulf Stream system between Cape Hatteras and 63° W. Long. and gives a qualitative analysis of the water masses in the surface layer on the basis of observations taken from November 15 to December 6, 1948. The edge of the Stream was explored for 1,050 miles of its length. The meanderings of the Stream and its tendency to develop large eddies are demonstrated. Of special note was the 90° change in direction of the mean axis of a 150-mile segment of the Stream within a period of two weeks. Surface current velocities are given for many points; flows in excess of 5.5 knots were found on several occasions. By means of a T-S analysis applicable during the period of the cruise, the surface layer of the system is described in terms of four water types. The occurrence and interplay of these water types are discussed. Noteworthy features are (a) the presence of Shelf water at certain points along the edge of the Stream and (b) the modification of the surface layer of the Stream by the addition of Sargasso water, with no evidence of the absorption of Slope waters.

INTRODUCTION

Although there have been many investigations of the Gulf Stream, it is only recently that detailed quasisynoptic surveys have been possible. This new approach is based on rapid measuring devices developed during World War II—the Bathythermograph (BT), the Sea Sampler (Spilhaus and Miller, 1948) and the Salinity-Temperature-Depth Recorder (Jacobsen, 1948; Ford, 1949) together with Loran which provides the necessary accuracy in navigation. The first surveys of the Stream with the BT and Sea Sampler were made by Spilhaus (1940, 1941), though without the benefit of Loran which had not yet been perfected. Following the war, rapid detailed surveys of the Gulf Stream were made using both the BT and Loran (Fuglister and Worthington, 1947; Iselin and Fuglister, 1948). These studies revealed that the highest current velocities tend to be associated with a sharp change in the temperature structure in the upper layers of the Gulf Stream and that the path of the Stream is of a meandering and variable nature.

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[1] This paper is a joint contribution from the Naval Research Establishment of the Defence Research Board of Canada, c/o Fleet Mail Office, Halifax, N. S. (Wm. L. Ford) and the Woods Hole Oceanographic Institution, Woods Hole, Mass. (A. R. Miller). Contribution No. 619 from the Woods Hole Oceanographic Institution.

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In our studies the above technique was extended to include the use of the Sea Sampler and the Salinity-Temperature-Depth Recorder. The general objective was to enlarge our meagre knowledge of the Stream by examining its meanderings and structure in as much detail and over as great a portion of its length as time would permit.

DATA

The area covered by the cruise from November 15 to December 6, 1948 is shown in Fig. 1. In all, 1,050 miles of the Stream were traced, 180 miles in the first survey and 870 in the second. Bathythermograms (660) were usually taken at half-hour intervals and to depths of 700–800 feet. Forty-three Sea Sampler lowerings yielded temperature traces to 450 feet together with an average of 10 salinity samples at each lowering to a depth of 320 feet. On the passage from Bermuda to Norfolk, Sea Sampler observations were made every four hours. Along the zig-zag route from Norfolk to Halifax, subsurface sampling was done usually on either side of the left edge of the Gulf Stream. Information on temperature-salinity (T-S) relationships obtained in this manner was supplemented by the continuous record of surface temperature and salinity obtained with a Salinity-Temperature-Depth Recorder (STD). Loran fixes were taken every 15 minutes, thus providing an unusually good body of navigational data.

The "inshore" or left edge of the Gulf Stream, looking in the direction of flow, is usually a sharp and well defined boundary characterized by an abrupt downward slant of the isotherms (see Fig. 4). In this paper the edge of the Stream is defined as the position at which the 65° isotherm reached a depth of 150 feet. The location of the inshore edge, and hence the path of the Stream, as found at various stages of this cruise is shown in Fig. 1 by the heavy line. The Stream itself lies to the right of this edge and flows more or less parallel to it. There is no well defined edge on the right-hand side.

The paths of the Stream shown in Fig. 1 tend to confirm the observations of Iselin and Fuglister (1948) and Church (1937) that the current not only meanders but that the meanderings develop progressively eastward from Cape Hatteras. Fig. 1 also provides some evidence on the rate of change of the Stream's path in that the mean axis of a 150-mile segment of it is shown as having changed direction by 90° within a period of two weeks.

The large swing east of 65° W. Long. is of particular interest. It is unfortunate that bad weather and a dwindling fuel supply made it necessary to terminate the survey without a full investigation of what appeared to be a large anticyclonic eddy centered on 64° W. Long.

and 39° N. Lat. In the centre of this eddy there is a submarine mountain that rises 10,000 feet above the surrounding ocean bed to within 6,000 feet of the surface. It is suggested that this submarine mountain may be a cause of large scale eddies in the Stream. A review of available data suggests that well developed meanders and probably eddies exist more often than not in this area (Iselin, 1936; Fuglister and Worthington, 1947; Iselin and Fuglister, 1948; Seven BT Sections, Halifax to Bermuda 1946–47, six of which showed two or more crossings of the edge of the Stream; Naval Research Establishment, unpublished data). It is particularly interesting to note that this eddy and the one implied in the drift of the VALOR are almost identical in size and location (Iselin and Fuglister, 1948). In 1945 the VALOR drifted for ten days in this area and navigational records kept by Lt. D. T. Parsons, U. S. N. R., were sufficiently accurate to permit the construction of a current diagram which indicated the presence of a great anticyclonic eddy centered at 64° W. Long. and 39° N. Lat.

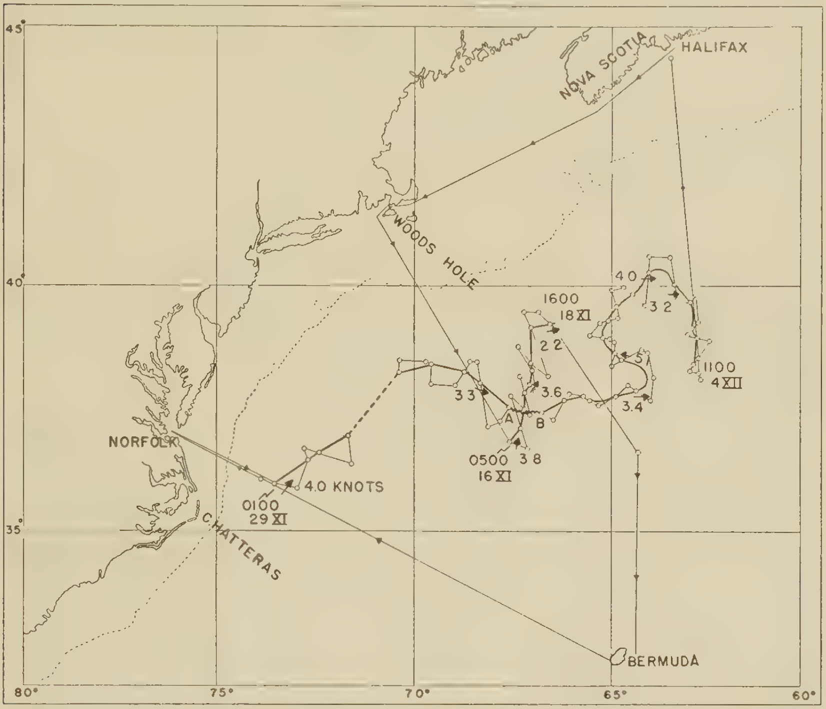
45°
40°
35°
80°
75°
70°
65°
60°
HALIFAX
NOVA SCOTIA
WOODS HOLE
NORFOLK
C. HATTERAS
BERMUDA
4.0
1600
18 XI
3.2
2.2
5
1100
4 XII
3.3
3.6
3.4
A
B
0500 3.8
16 XI
4.0 KNOTS
0100
29 XI

Figure 1. Gulf Stream Cruise NL–16, Nov. 10 to Dec. 6, 1948. The heavy line is the "inshore" edge of the Stream. The light straight lines are the course of H. M. C. S. NEW LISKEARD.

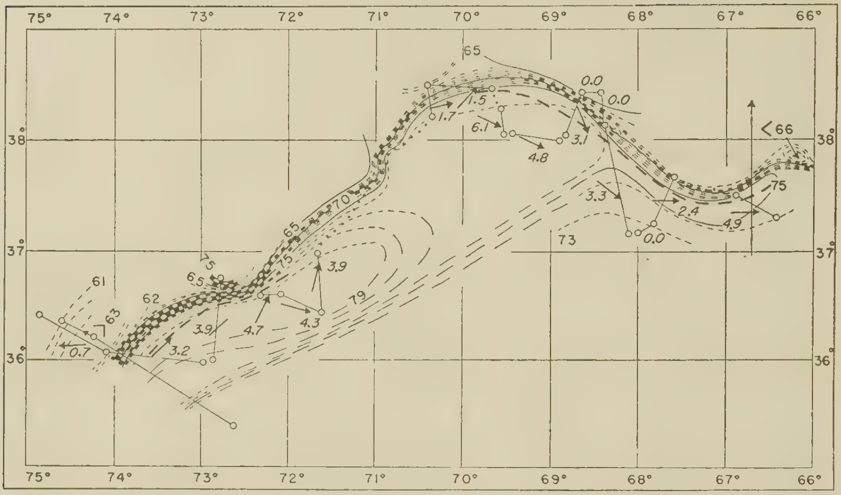

Figure 2. Surface temperature contours of a part of the Gulf Stream. The heavy dotted line is the edge of the Stream at a depth of approximately 150 feet. The arrows give the current direction and the adjacent numbers its speed in knots. The light straight lines are the ship's course.

To show surface temperatures and current velocities in necessary detail, the survey was divided into three parts, two of which are presented in Figs. 2 and 3. The third part, which is that section surveyed November 15–18, is omitted. The arrows give the direction of the current and the adjacent numbers show its speed in knots. The directions are the resultant of the vectors, dead reckoning course and true course, as determined by Loran fixes. The speed is the quotient of the resultant divided by the time. No allowance was made for wind drift. The fine straight lines give the actual ship's course as determined by Loran. The given velocities are averages for each leg. The terminals of the legs do not necessarily represent a change in compass course of the ship; in some cases they represent an alteration of the actual course by an abrupt change in current. Currents in excess of 5.5 knots were observed on several occasions. Although this method of determining surface current is crude, the data were carefully examined and it is believed that the above figure is reasonably correct. Fuglister and Worthington (1947) and others have also reported such values.

The vertical temperature distribution down to 800 feet was obtained by means of the BT every half hour during most of the cruise. Since it is impractical to present such a mass of data, a reasonably typical sample is presented in the form of two sections in Fig. 4.

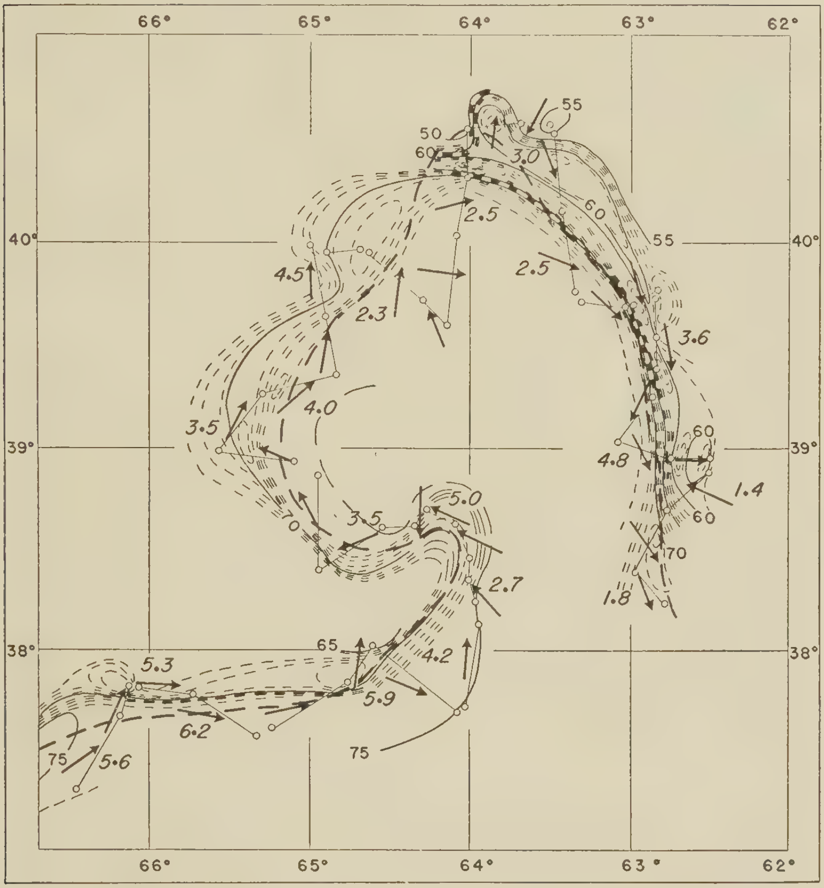
66°
65°
64°
63°
62°
40°
39°
38°
55
50
60
3.0
2.5
60
55
4.5
2.3
2.5
3.6
4.0
3.5
60
4.8
1.4
60
70
3.5
5.0
70
2.7
1.8
65
4.2
5.3
5.9
6.2
75
75
5.6

Figure 3. Eastward continuation of Fig. 2.

The surface temperature characteristics of the Stream were as shown in Figs. 2 and 3. The warm core, with a maximum temperature of 80° F off Cape Hatteras, had cooled to less than 76° F on reaching 68° W. Long., but eastward of this point its temperature remained quite constant at 75 ± 0.5°.

The waters on the cold side of the front were mostly in the middle sixties except at the most northerly limits of the system. One such situation is shown in Fig. 3 at 64° W. Long., where a temperature of 50° F was found close to the front. Another similar case was found at 67° W. Long. and 39° 30′ N. Lat. during the earlier part of the survey. The nature of these cold waters will be discussed in the next section.

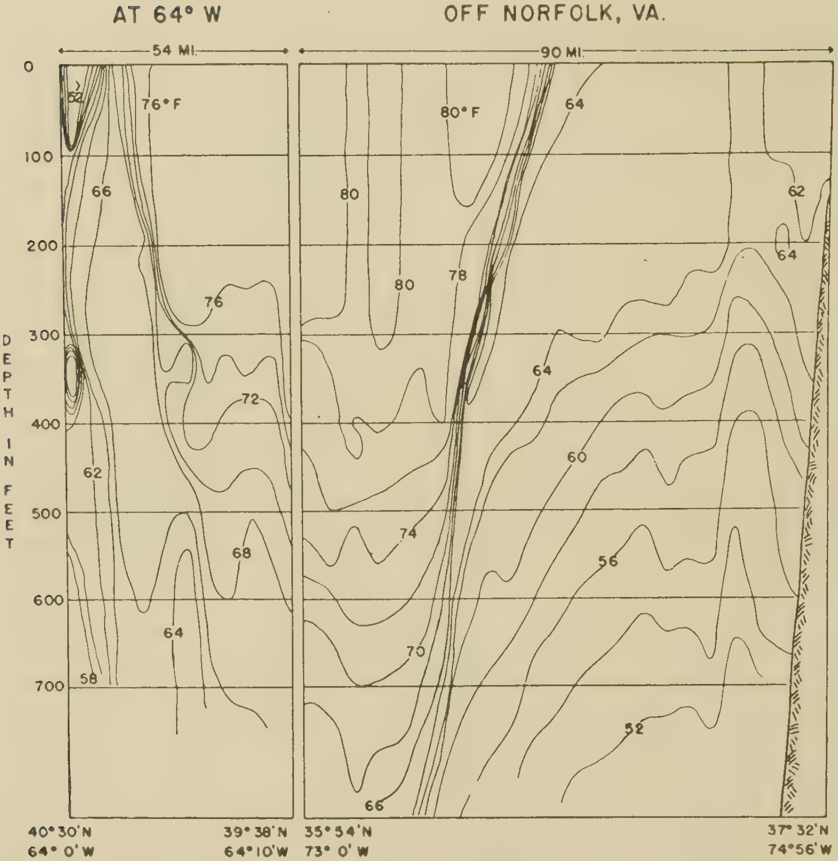

Figure 4. Two examples of B-T temperature sections showing the edge of the Stream.

SURFACE WATER MASSES OF THE STREAM

A T-S analysis of the surface layer from data provided by the STD and the Sea Sampler has proven useful in developing a qualitative analysis of the water masses involved in the system. Such an analysis is subject to the criticism that the temperature under these conditions is not a conservative property but may in fact be subject to changes due to diurnal heating and cooling, meteorological changes, and seasonal trends. It is believed that the latter can be ignored, since the data were collected in a period of less than three weeks. The passage of weather would not be expected to produce serious errors because of the moderating influence of the ocean. Diurnal effects

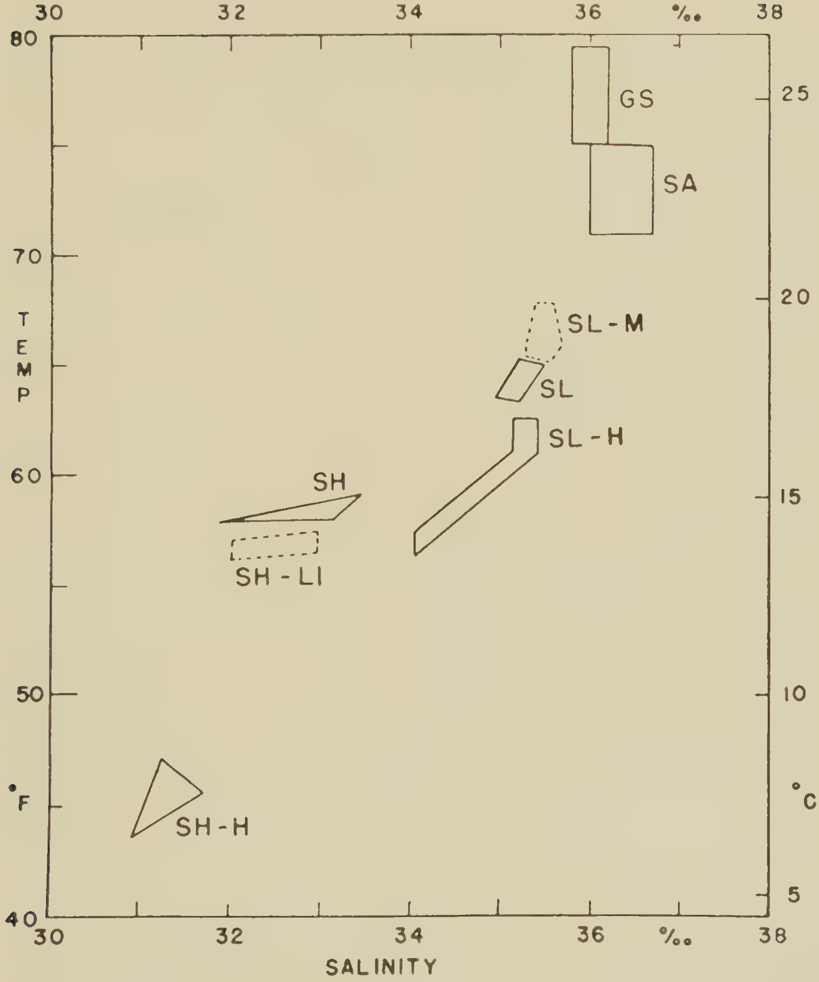

Figure 5. T-S relationships of the water masses of the surface layer of the Gulf Stream system. SH, SL and GS are respectively Shelf, Slope and Gulf Stream waters east of Norfolk, Va. SH-H and SL-H are respectively Shelf and Slope waters south of Halifax. SH-LI is Shelf water off Long Island. SL-M is Slope water south of Montauk Pt. SA is Sargasso Sea water. See text for details.

appear to be negligible, probably due to the low altitudes of the sun in November and December and to the turbulent character of the system. T-S diagrams showed a considerable scatter, which can be attributed in part to these factors and in part to the uncertainty (± 0.2°/₀₀) in the measurement of salinity by the STD. Nevertheless, it is apparent that these uncertainties do not mask the main features. This is in agreement with Miller's (1950) conclusions on a similar use of T-S analysis. The main features are illustrated in Fig. 5, which is a T-S diagram that defines the surface water masses involved in this analysis. It provides a means of describing any given mixing zone in terms of two or more of these basic water types.

This diagram was obtained by plotting a large number of S-T observations taken from the STD record, and then, with the surface patterns of Figs. 2 and 3 in mind, those points which fell into characteristic groupings were enclosed in the manner shown. From a study of BT, STD and Sea Sampler records, it can be shown that these groupings, though necessarily somewhat arbitrary, represent reasonably homogeneous water masses.

Referring again to Fig. 5, Shelf water (SH) was defined as that which was found between 75° and 75° 30′ W. Long. on the course out from Norfolk, Va. Waters inshore of the latter point were not included, since they were of very low salinity and probably contained Chesapeake Bay outflow. Slope water (SL) was defined as that which lay between 74° and 74° 30′ W. Long. on the same course.

Gulf Stream water (GS) was defined by salinities and temperatures taken in the "core" of the Stream, in an area extending from off Cape Hatteras to about 66° W. Long. GS water is characterized by a salinity of $36 \pm 0.2^{\circ}/_{\circ\circ}$ and by a temperature $>$ 75° F. Sargasso water (SA) was defined by observations taken on the course from the Gulf Stream towards Bermuda to about 35° N. Lat. and between Bermuda and Norfolk. It is characterized by a salinity $> 36.0\ ^{\circ}/_{\circ\circ}$ and a temperature $<$ 75° F. Surface water off Long Island (SH–LI) and surface Slope water south of Montauk Pt. (SL–M) are represented in a section from 71–72° W. Long. at 39° 50′ N. Lat. as reported by Miller (1950) for cruises of the Albatross III and Caryn in October and November 1948. Although these data were obtained one month before the New Liskeard cruise, they appear to be applicable to this analysis and are included to round out the picture. Furthermore, they are the only available data for this area, since no salinities were obtained in Cruise NL–16 on the run out from Woods Hole until 38° 30′ N. Lat. was reached. However, beyond this point, while still in Slope water, recorded STD salinities and temperatures fitted the SL–M grouping.

Slope water south of Halifax (SL–H) is a grouping based on observations taken on the return trip to Halifax between 40° N. Lat. and the 100-fathom line. It was the most difficult to define, and the grouping finally chosen appears to contain Shelf water—Halifax (SH–H). This latter water mass, quite clearly defined, represents the surface water as found while traversing the Scotian Shelf to Halifax.

A number of Sea Sampler stations have been analyzed to indicate the vertical extent to which the surface T-S analyses apply. The position of these stations are shown as circles in Figs. 6 and 7. Those Sea Sampler stations taken in the Stream (Nos. 3, 4, 6, 8, 10, 12, 13) show, with exception of No. 13, that the water was homogeneous from the surface down to 317 feet, the maximum depth of the Sea Sampler. No. 13 revealed homogeneous surface water (GS + SA) down to 200 feet and SA water below that. Sea Sampler stations taken in clearly defined Slope water (Nos. 2, 9, 14) showed a homogeneous water column to the maximum depth, 317 feet. The remaining stations (Nos. 1, 5, 7 and 11) were in boundary zones. No. 1 shows a homogeneous layer of SH + SL water 150 feet thick over SL water. No. 5 reveals a complex situation with a uniform mixture of GS + SH to 100 feet and then a transition layer passing through SL water at 200 feet to a higher salinity water at 250 feet. Nos. 7 and 11 show homogeneous mixtures of GS + SL and GS + SA + SL respectively to the maximum depth of the Sea Sampler.

In the open ocean, if a BT section reveals an isothermal surface layer, it is generally recognized that the layer is in fact also isohaline and may be considered homogeneous. The BT data of this cruise did show in general a mixed layer of more than 200 feet except in transition zones. Fig. 4 is an example that illustrates the point. On the basis of these considerations, it is assumed that surface salinities and temperatures represent an homogeneous layer, which was usually more than 200 feet thick throughout the area covered by the cruise. This statement, of course, is applicable only during the period of the cruise, since the mixed layer undergoes a seasonal variation, being deepest in midwinter and shallowest in midsummer.

In Figs. 6 and 7, the water masses described above are presented in their geographical relationship, and we may now see which water masses were involved in zones of mixing and how the system changed character from west to east.

The sections off Norfolk are of particular interest because of the presence of Shelf water (coastal) at the edge of the Stream. In Fig. 7 it will be seen that there was a narrow band of water of less than 63° at the edge of the Stream. Its T-S characteristics show that it was a mixture of SH and GS waters, mostly SH, and contained no SL water. The temperature section[2] (Fig. 4) suggests that it had a vertical extent of nearly 400 feet at the position of the section. The band was traced for about 80 miles along the edge of the Stream. The edge was not crossed again until a position some 140 miles further

[2] This diagram is uncorrected for temperature; correction is − 1.0° F.

along had been reached, and at this point, 70° 30′ W. Long., no evidence of Shelf water was found.

The presence of Shelf water along the edge of the Stream is explained by considering that the Shelf water flows southward on the continental shelf, turns eastward off Cape Hatteras and inserts itself between the Stream and the Slope water—eventually to be absorbed.

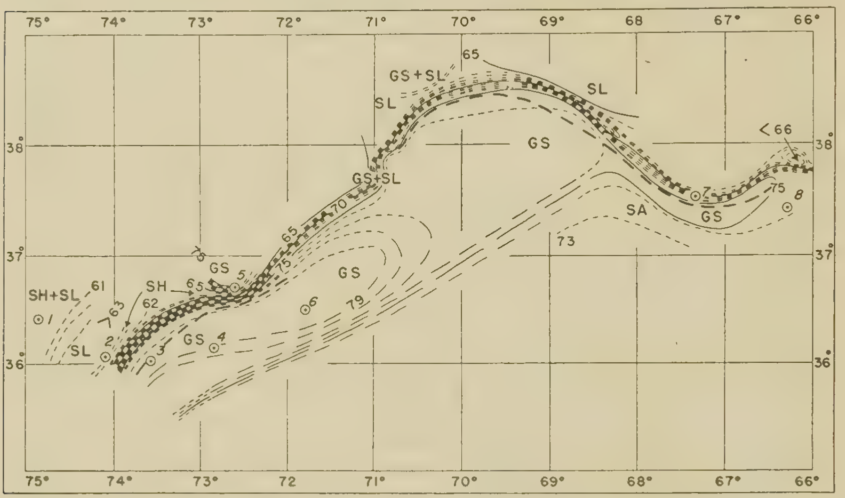

Figure 6. Surface temperature contours of a part of the Gulf Stream with the surface layer water types indicated. The numbered circles are Sea Sampler stations.

To strengthen this explanation, it is noted that the T-S characteristics of this water were such that it could not have risen from the depths; nor could it have come from coastal areas south of Hatteras. Hydrographic studies of that region in 1948 (Bumpus and Wehe, 1949) showed that there is little or no transport of Shelf water either north or south around Hatteras. These considerations agree with the concept that Cape Hatteras is a boundary zone between two distinct regimes upon the continental shelf. Therefore it is concluded that the low salinity water found at the edge of the Stream did originate on the shelf north of Hatteras.

It is of interest to note the appearance of SA water between the Stream proper and the 70° surface isotherm in the edge zone at several points within the great eddy. Consider, for example, a section through the edge at 63° 30′ W. Long. and 40° N. Lat. (Fig. 7). Beginning at a point to the north of the front and proceeding southward, the following waters were found: first a mixture of SH-H and SL-H, then a transition zone which included SL-H (35.5 °/₀₀ and 63° F),

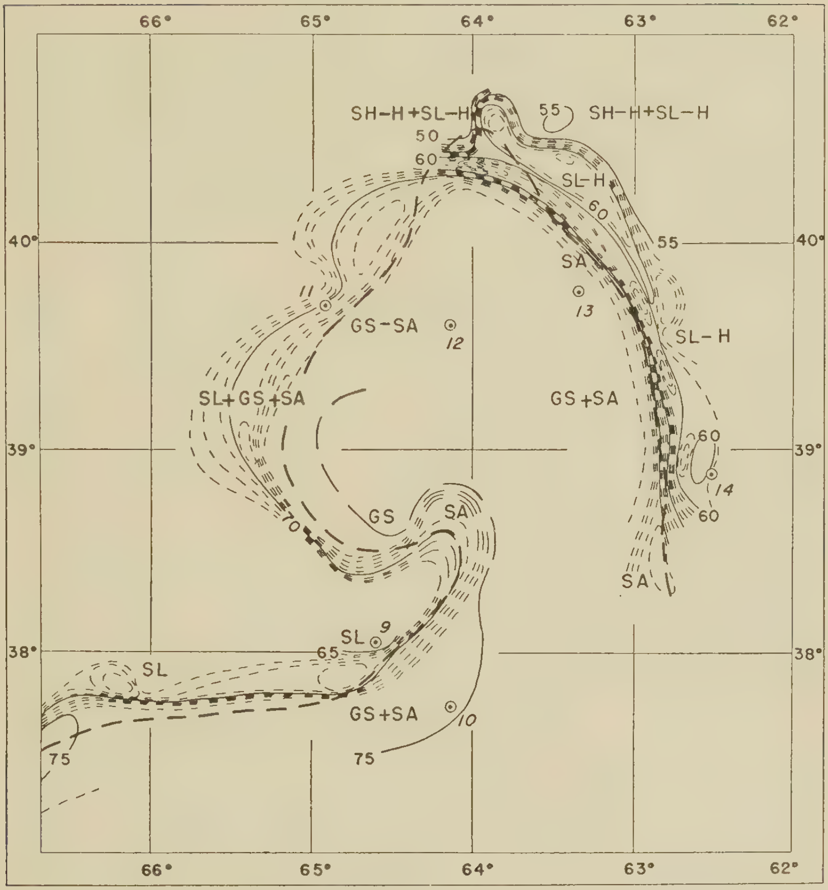
66°
65°
64°
63°
62°
40°
39°
38°
SH-H+SL-H
55
SH-H+SL-H
50
60
SL-H
60
55
SA
13
SL-H
GS-SA
12
SL+GS+SA
GS+SA
60
14
60
GS
SA
70
SA
SL
9
65
SL
GS+SA
10
75
75

Figure 7. Eastward continuation of Fig. 6.

and then, very abruptly, SA water (36.25 $^{\circ}/_{\circ\circ}$ and 70° to 74° F). Next a gradual transition to a mixture of GS-SA waters (36.25 $^{\circ}/_{\circ\circ}$ and 75° F) was found. The density of the SA water is greater than that of the adjacent Stream but less than that of the Slope water.

Two interpretations as to the origin of this SA water may be considered: (1) it merely represents a mixture of GS-SA which has cooled a few degrees; (2) it actually represents SA water that had crossed the surface waters of the Stream at some depth and upwelled. Although there is not sufficient information to prove either point, the latter seems more acceptable. It has been shown that the SA water probably extends downward several hundred feet, and if this is so, it is not likely that surface cooling could account for the lower temperature. Sea Sampler station No. 13 (Fig. 7), which was taken at the Gulf Stream end of the section discussed above, revealed SA water (70°–74° F and 36.4 °/₀₀) below a warmer and less saline surface layer, thus indicating the presence of a source for upwelling SA water.

At the most northerly reach of the Stream (Fig. 7), water of less than 55° F was encountered. This water proved to be a mixture of SH-H and SL-H waters. It is remarkable that Shelf water should be found so far offshore.

The T-S analysis shows the nature of the modification in the surface layer of the Stream as it flowed eastward. Downstream from Hatteras the temperature decreased, but there was no significant change in salinity and the water remained within the definition of GS water until 65° W. Long. was reached. In this neighborhood GS water as such disappeared (see Fig. 7) and was replaced by a mixture of GS-SA, which from this point on showed the general character of the water in the core of the Stream. That is to say, the surface salinity and temperature in the Stream proper, as recorded by the STD, fell in a narrow band encompassed by the GS and SA blocks as given in Fig. 5. It is clear also from Fig. 5 that if any appreciable amount of Slope water were included in the core of the Stream the T-S points would fall below the SA block. Such was not the case. In summary, as the stream moved eastward it appeared to be modified by the addition of Sargasso water. There appeared to be no absorption of Slope water.

Turning now to the Slope water adjacent to the Stream, the transition of its characteristics from west to east is shown in terms of T-S relationships in Fig. 5 and geographically in Figs. 6 and 7. Up to at least 65° W. Long. and 38° N. Lat. the Slope water is of the "Norfolk" type (SL). From this point to about 40° N. Lat. the ship's course did not extend far enough beyond the front of the Stream to clearly define the Slope water; but beyond this latter point, Slope waters adjacent to the Stream were of the "Halifax" type (SL-H). The two waters are outstandingly different in that the SL water was a homogeneous mass defined by a small range of salinity and temperature, whereas the SL-H water was found not as a clear-cut mass but in patches interspersed with mixtures containing water of the Scotian Shelf type (SH-H).

If that part of the SL-H block (Fig. 5) above 35 °/₀₀ is considered to be Slope water adjacent to the Gulf Stream, then SL-H and SL water differ only in temperature. Mere surface cooling could transform the latter into the former on the assumption of an easterly flowing Slope current adjacent to the Stream, as is postulated by Sverdrup, et al. (1942). On the other hand, if the Slope water adjacent to the Stream moves westerly as a counter current, then the Slope waters in the westerly part of the area (SL) could result (Fig. 5) from the mixing of Stream water (GS–SA) with easterly Slope water (SL-H), providing it contains that part of the block below 35 °/₀₀.

The latter provides a more consistent interpretation, for when it is considered in conjunction with the evidence that the Stream absorbs Sargasso water but not Slope water, it leads to qualitative agreement with Rossby's (1936) wake stream theory. This theory requires that the Gulf Stream should absorb water from the oceanic areas to the right of the current and discharge water into a counter current on the left.

ACKNOWLEDGMENTS

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Contribution No. 621

Särtryck ur Tellus nr 3, 1952

Notes on the Surface Velocity Profile and Horizontal Shear across the Width of the Gulf Stream[1]

By WILLIAM S. VON ARX
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(Manuscript received 1 August 1952)

Abstract

During a cruise across the Gulf Stream in October 1950 measurements of surface velocity were made both with the Loran-~~space~~ DR method and the electromagnetic method. A short account of the results is given with special reference to the velocity profile and the horizontal shear across the Gulf Stream.

The transverse surface velocity profile

In October, 1950, a short cruise was made across the Gulf Stream south of Cape Cod to observe the transverse surface velocity profile. Current velocities were observed by means of dynamic sections (Atlantic stations 4853 to 4865), the Loran ~~space~~ dead reckoning method, and the electromagnetic method (VON ARX, 1950). A preliminary reconnaissance of the area revealed an anticyclonic bend which was then crossed repeatedly at nearly right angles to the flow. Some of the results, shown in Figure 1, disagree among themselves but suggest the narrow width and sharply peaked form of profile which seems possibly to be characteristic.

Disagreement among observations stems partly from the average error of Loran, which at a range of several hundred kilometers from the transmitters amounts to about ± 1 kilometer. This amount of uncertainty in the position of each hydrographic station and of the drift of the ship while on station in the strongest part of the current, leads to a relative error

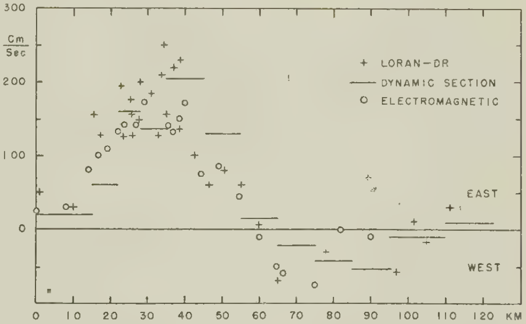

Fig. 1. Comparison of simultaneous measurements of surface velocity across the width of the Gulf Stream near the 69° W meridian, made by navigational, dynamic, and electromagnetic means. The area under a curve drawn through the eastward phase of each set of observations is 6.2, 6.0, and 5.4×10^8 cm^2/sec., respectively. The dynamic observations were made and computed by Mr. L. V. Worthington. All observations made in October 1950 from R. V. ATLANTIS.

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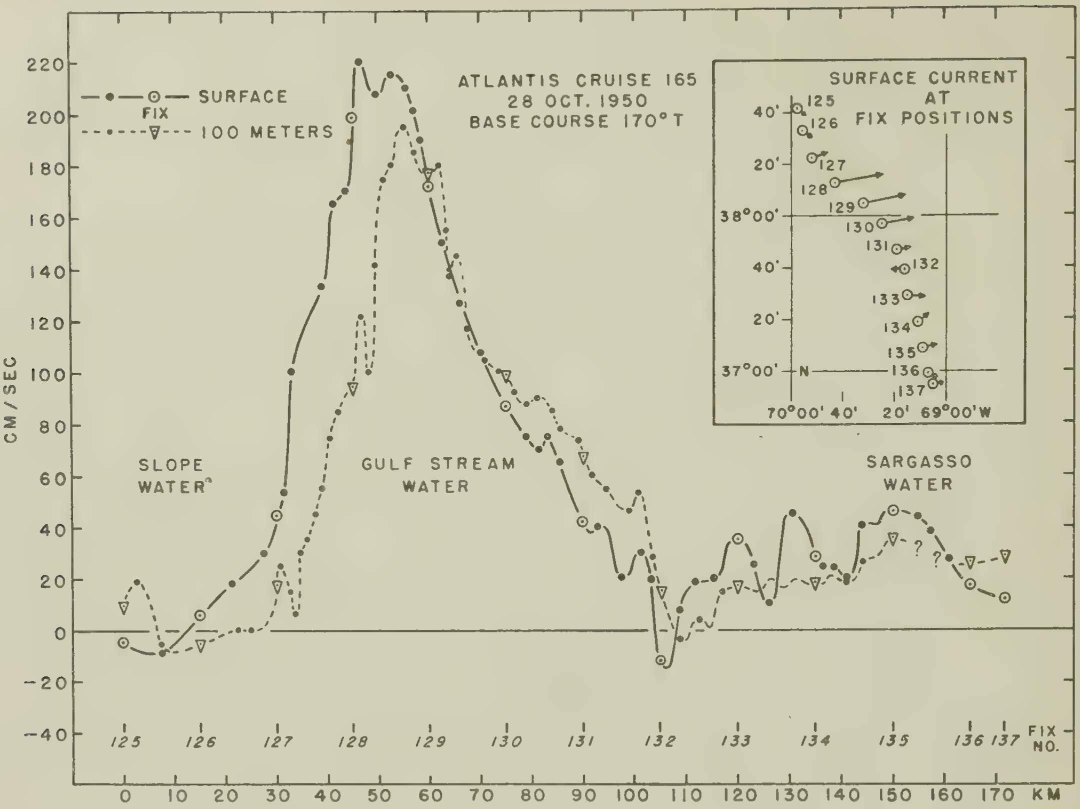

Fig. 2. Results of simultaneous electromagnetic measurements of the velocity at the surface and 100 meter levels. Open symbols denote points at which the direction of flow was measured. Closed symbols and the trend of the lines joining them denote the current speed at intermediate points assuming that the direction remained the same or changed uniformly between fixes of direction. The abscissa was taken at right angles to the direction of flow at fixes 128 and 129. The ordinates shown are 23 per cent less than the average of navigational measurements of current speed.

in the distance between stations 5 km apart perhaps as great as 20 or 30 percent. Similarly the errors of Loran and dead reckoning for navigational current measurements made on an hourly basis, may approach 50 cm/sec and become proportionally larger as the time interval is decreased. Measurements of surface current by the electromagnetic method are reduced in magnitude when the current structure extends downward through more than a negligible fraction of the total depth of water (STOMMEL 1948; MALKUS and STERN 1952). In that the current structure of the Gulf Stream may extend a kilometer or more below the surface, and the loss of signal strength is roughly proportional to the ratio of the depth of quiet water below the current to the total depth, decrements as great as 40 percent are sometimes encountered in the Gulf Stream off the New England coast.

In the face of these uncertainties it has been necessary to counteract the limitations of one method with the advantages of another. In fine weather the evidence of navigation is a useful index of surface motion, but the method lacks resolving power. The electromagnetic method will indicate direction of flow and detailed changes in one component of motion, but requires calibration in magnitude. Both methods can be used underway.

Figure 2 shows the uncorrected results of electromagnetic sections made simultaneously at the surface and 100 meter levels. Navigational measurements made on the same traverse indicate that the electromagnetic measurements of surface current speed averaged 23

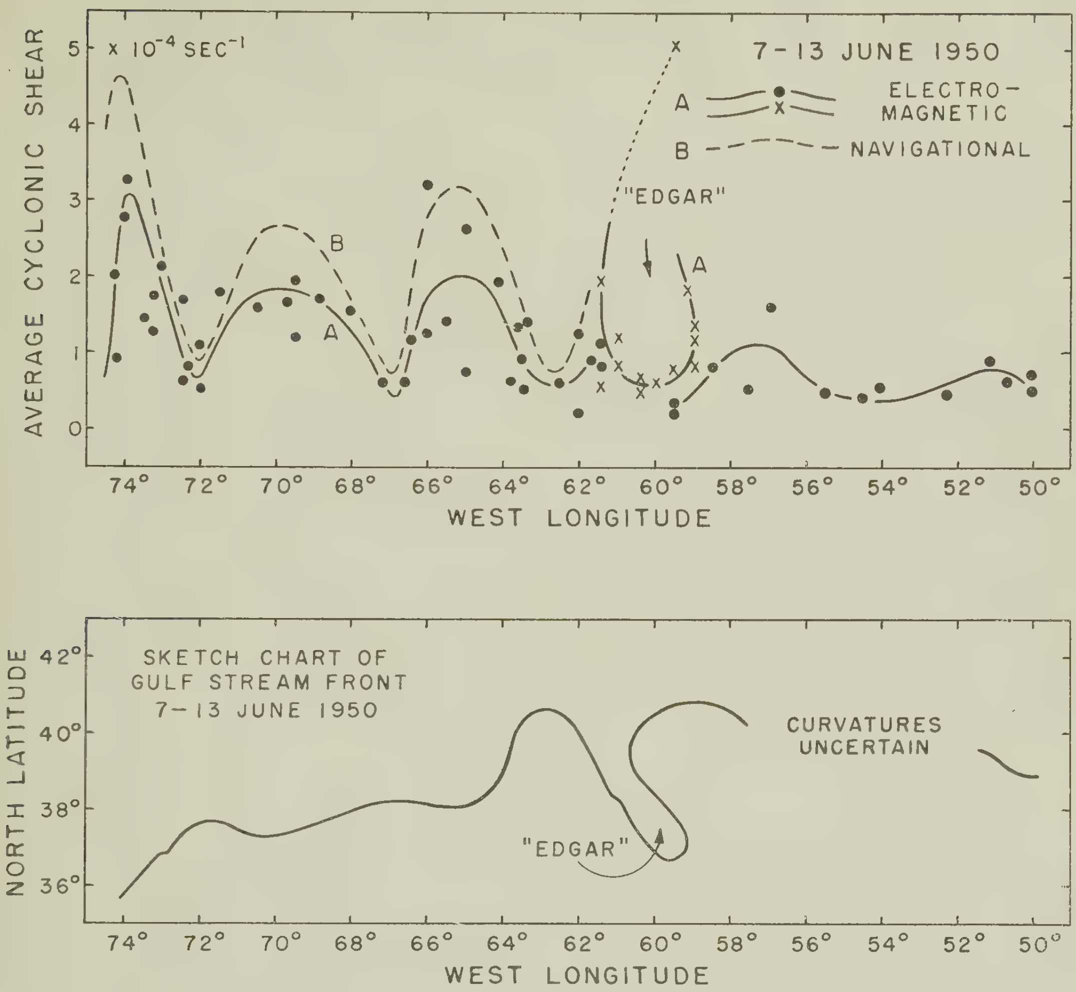

Fig. 3. Comparison of the intensity of cyclonic shear (between the Gulf Stream front and the current maximum) with the curvature of the front. Curves A and B in the upper frame represent the smoothed results of electromagnetic and navigational measurements of shear, respectively. The chart of the position of the Gulf Stream front in the lower frame was made from measurements of the greatest change of average temperature in the upper 200 meter layer. "Edgar" is a deep cyclonic bend that was observed to detach from the main current. Within this feature navigational measurements of shear were 1.7 times greater than electromagnetic measurements.

percent too small. Nevertheless a sharply peaked distribution of velocity across the current seems evident. The similar pattern of motion at the 100 meter level was displaced to the right of the surface profile along a seaward slope of approximately 1/80. The horizontal normal shear on either side of the current maximum was asymmetrical.

Horizontal shear

Data obtained during the multiple ship survey of the Gulf Stream of 1950 (FUGLISTER and WORTHINGTON, 1951) made possible a study of the change of the intensity of horizontal shear along the meandering current. The intensity of shear was first evaluated from a comparison of Loran and dead reckoning navigation, and then corrected for the local obliquity of the traverse to the direction of flow as indicated by electromagnetic measurements. In order that the curvature of flow might be neglected, the shear was evaluated and corrected for the obliquity of traverse to the direction of flow in increments of one or two hour's run.

It was found that the average intensity of horizontal shear normal to the flow on the right of the current maximum was equal to or less than the Coriolis parameter, while the average values of cyclonic shear on the left were equal to or greater than this. Such asymmetry of shear has been suggested from theory by HAURWITZ and PANOFSKY (1950).

These data from the multiple ship survey also show that the intensity of cyclonic shear on the left of the current maximum varies systematically with the sense of curvature of flow. Greater than average intensities seemed to be associated with cyclonic curvatures, while less than average intensities seemed to occur where the sense of curvature was anticyclonic. Due to the unsuitable distribution of observations, it was not possible to test for a similar correspondence of curvature with the intensity of anticyclonic shear on the right of the current maximum, or for the persistance of a seaward counter current.

In Figure 3 the upper frame contains the measurements of horizontal cyclonic shear, and the lower frame a schematic chart of the curvatures of the Gulf Stream front during the period when these observations were made. It can be seen from a comparison of the curves in the upper and lower frames that the intensity of shear does not seem to depend on the length of the radius of curvature of flow. The points through which curve A was drawn represent electromagnetic measurements of shear, and curve B represents the smoothed result of the navigational measurements. There is a systematic increase in the proportion of disagreement between the electromagnetic and navigational estimates of shear in the vicinity of cyclonic curvatures which suggests that the current extends to greater depths in the vicinity of cyclonic curvatures. Such an interpretation is consistent with an increase in cyclonic shear since vertical stretching and horizontal convergence of the flow in cyclonic curvatures would result in increased cyclonic vorticity on the left of the current maximum. There is some evidence that the current maximum itself shifts toward the left as well as that surface current speeds are a little higher in cyclonic curvatures of flow.

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Särtryck ur Tellus nr 4, 1952

A Laboratory Study of the Wind-driven Ocean Circulation.[1]

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(Manuscript received 10 August 1952)

Abstract

Experiments with rotating oceanographic models are being attempted in the laboratory at Woods Hole in the hope that some information may be gained which will help to close the gap between recent theories of ocean circulation and the observed nature of the circulation. Recent theoretical descriptions by STOMMEL (1948) and MUNK (1950) indicate the broad features of the climatological mean circulation pattern. In contrast, observations usually allow description of possibly transient situations in only relatively small regions. The major observational problem at the moment, short of synoptic measurements over large areas, is to learn how the observations made from moving ships fit into the pattern of very large scale fluid processes.

Some insight has already been gained through the search for atmospheric counterparts initiated by Dr C.-G. Rossby, and it is hoped that a wind-driven model of the oceans may offer additional clues. It is recognized that ocean models cannot be scaled in every particular and that the scales taken into account may lead to error since processes of verification, ordinarily used to test the suitability of hydraulic models, cannot be applied. Thus the behavior of a rotating model can bear a limited resemblance only to contemporary ideas of what the primary ocean circulation may be like.

In terms of these ideas, however, it has been possible to reproduce westward intensification of the primary circulations in compartments shaped like the North Atlantic and North Pacific basins. Sargasso Sea-like features and several details have also appeared which are qualitatively like contemporary views of the major motions of the sea. These major, and some minor features of the circulation develop rapidly under wind-stress applied to homogeneous water.

1. Description of the apparatus

A basin having the internal form of a paraboloid of revolution was chosen because it provides a Coriolis parameter which varies with latitude, and a free liquid surface which is accessible for the application of wind stress, heat, light, and tracer materials. In a paraboloid of reasonable depth, however, the Coriolis parameter does not ordinarily approach zero at the rim. Therefore, experiments are generally limited to extratropical regions unless geometrical and dynamical distortions of various sorts are allowed. Figure 1 shows the arrangement of parts.

a) The mechanical system

The paraboloidal basin now in use is 2 meters in diameter and has a focal length of 0.5 meter. The paraboloid rises from the vertex to the latus rectum, then enters a toroidal section and is terminated in a cylindrical

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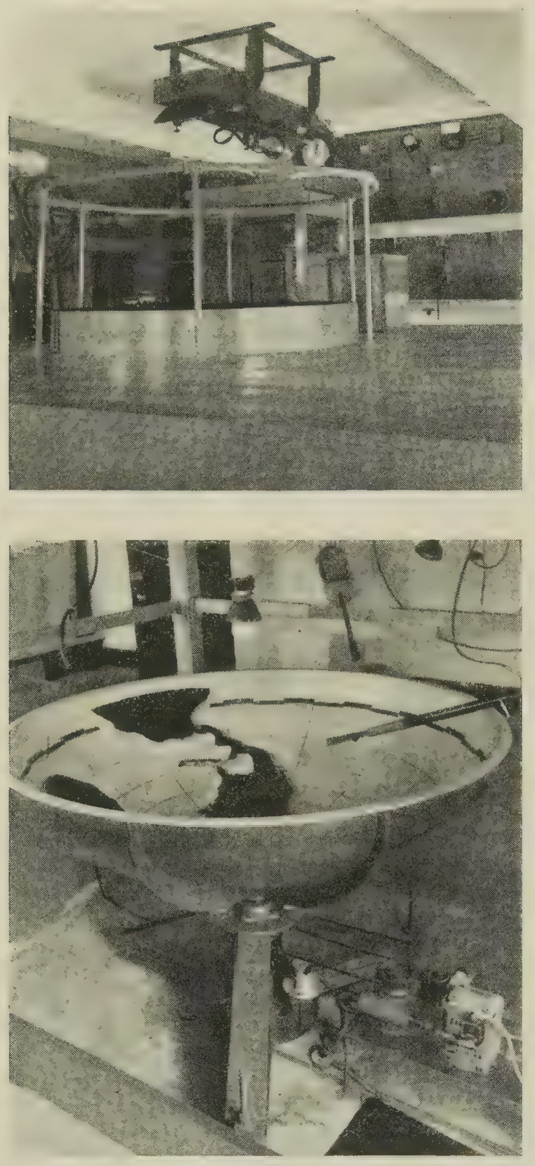

Fig. 1. General arrangement of the rotating basin apparatus. The control panel at the extreme right is accessible from the observers desk at the eye end of the optical train. The basin itself is mounted in a concrete sump below the observation platform. The drive machinery can be seen at the lower right. The main light at the effective center of curvature of the basin and the blowers around the basin are suspended from the platform. The continental modeling is 6 cm high and cemented in place.

section extended high enough to prevent a layer of water 10 cm deep from overflowing at the equilibrium rate of rotation. The basin is made of fiberglass bonded with a plastic. Eight ribs are bonded to the basin and to a stainless hub at the vertex. The basin weighs about 80 kilograms and will support a 500 kilograms load of water.

The basin is mounted on the end of a vertical shaft 10 cm diameter by 0.6 meter high, fitted snugly into two self-aligning radial-thrust bearings in a heavy, welded steel tripod which is secured to a concrete slab by nuts on three leveling screws embedded in the slab. The drive for the basin consists of a 1 H.P. capacitor-starting synchronous motor which drives the basin through a variable-ratio V-belt speed controller and a worm gear speed reducer. The basin shaft is coupled to the drive by a V-belt which has proven satisfactory when run with considerable slack. Once the basin has been accelerated to speed, it runs nearly free of the drive machinery except for the small amounts of power required to overcome friction and air resistance. The equilibrium rate of rotation of the basin is 3.13 radians per second, hence the tangential velocity of the rim is over 3 meters per second. Even so, the water in the basin remains quiet and the free surface is smooth except for the wind ripples which become noticeable in the zone within 20 to 35 cm of the rim. These ripples can be damped out by means of a detergent on the free surface. To avoid seiches the vertical shaft carrying the basin must be quite plumb.

b) The optical system

The optical system for observing the circulation in the basin and illuminating it requires consideration. In the Woods Hole installation, where there is only limited head-room, the entrance pupil of the optical system was, o necessity, placed 2.5 meters above the vertex of the paraboloid, hence a true field of 60° was required. This was accomplished by viewing the basin through the "wrong end" of a surplus M71H tank telescope having a 65° apparent field, focused so as to produce a beam of parallel rays emerging from the objective end. This places the image of the basin at infinity. Derotation of the image is accomplished with a Dove prism. This component, mounted in precision ball bearings, was placed in emergent beam and rotated by means of a selsyn repeater motor driven by a similar selsyn motor linked to the basin shaft by a rubber belt. The sheave ratio at the basin shaft was made 1/3 and the sheave ratio at the Dove prism 6/1, so that the Dove prism revolves at one-half of the basin rate regardless of the angular velocity of the basin, while the selsyns themselves turn over at a more efficient rate. It was found expedient to provide the Dove prism sheave with a cylindrical face and the repeater selsyn sheave with a 90° groove so that small changes required to adjust the ratio of these two sheaves could be effected by changing the tension of the round rubber belt connecting them.

A Dove prism must be placed in a beam of parallel light, so that the aberrations introduced at the first refracting face are exactly cancelled by the second. A Schmidt prism, or an equivalent system of plane mirrors, may be used if parallel light cannot be managed. Both prisms offer an odd number of internal reflections (one in the Dove prism and five in the Schmidt prism) so that an additional reflection is required to revert the image. This added reflection was obtained from a plane first-surface mirror ahead of the entrance pupil. This proved to be a convenient way to change the axis of the optical system from vertical to horizontal under low head-room conditions.

The parallel beam emerging from the Dove prism provides a stationary, real image at infinity which has only a small angular size due to the negative magnification of the reversed telescope. This image can be examined comfortably through a second telescope or photographed directly if lenses of suitably long focal length are used to cause the image to fill the frame. Exposures longer than one second have been possible. The light losses in the optical train amount to about 60 per cent.

Time lapse motion pictures have been made through this optical system which are synchronized with the rotation of the basin. A microswitch trips the camera electrically as it is engaged by combinations of 16 pins of different lengths concentrically arranged on a disc turning with the basin shaft. Of the 16 pins, one is longest, one is located at 180° from the first and is made a little shorter, two at 90° to the first pair are equal in length but shorter than the second mentioned, four still shorter pins are located at the 45° positions, and the eight shortest pins are located at the 22.5° positions. Thus by simply raising and lowering the micro-switch the camera can be tripped 1, 2, 4, 8, and 16 times per basin revolution regardless of the angular velocity of the basin. A small light mounted at rest in the field of view appears as a streak in each exposure indicating the angular motion during and between exposures. The duration of exposures and time elapsed between them can be measured in this way.

The main source of illumination is a 2000 watt lamp. The lamp is placed at the effective radius of curvature of the paraboloid so that the illumination is quite uniform and reflections from the free surface are returned to the light source.

The optical system is supported independently so that the vibrations of machinery do not disturb it, and the activities of the observer do not change its alignment with the axis of rotation of the basin.

c) The pneumatic system

The air streams over the model which are used to simulate atmospheric circulations are produced by three tank-type vacuum cleaners operating wrong-end-to as blowers, and spaced 120° apart around the basin. When equipped with nozzles these blowers can be aimed at limited zones of the paraboloid to increase or decrease the local relative motion of air beyond that due to the rotation of the basin. A variac controls the speed of all three blowers simultaneously. Suitable wind torques can be achieved either by directing the blowers so as to produce westerlies in temperate latitudes or easterlies in the trade wind zone. The latter requires smaller discharge velocities from the blowers and is more generally used.

d) Tracers

The matter of tracers for the detection and measurement of water motion is unsettled. Neutrally buoyant ink, potassium permanganate, aluminum tristearate, n-butyl phthalate and xylene, aluminum foil and several other substances (including cranberries) have been used at different times. The ink-potassium permanganate combination is useful since the ink stays near the surface and the permanganate crystals sink to the bottom to produce trails of color. In regions of upwelling the permanganate solution oxidizes the ink and changes the color of the mixture. The latter three tracers are essentially particulate but none has a high enough albedo to permit satisfactory streak photographs to be made with the present apparatus. An interesting alternative to streak photographs has been proposed; namely, if the two instantaneous photographs taken at slightly different times, the stereoscopic relief of displaced particles or dye fronts would be proportional to the velocity. In this manner a velocity solid might be visualized or constructed.

e) Comments on design

The design of the mechanical and optical systems for this rotating basin apparatus was exploratory, and can be improved in many ways. For example: ultra-wide field astronomical optical systems exist which, with a Schmidt prism for derotation, would be an improvement over the rather crude optical system now in use. Similarly, the frequency controlled synchronous telescope drives already in use in some observatories could be adapted to the basin drive to afford not only a steadier motion but better control and measurement of the angular velocity. Wind stresses should be applied in a more elegant manner than at present, and should be subject to better quantitative control. The matter of suitable tracers for the detection and measurement of circulation at all levels requires more study.

2. Scaling and modeling

An oceanographic model requires that certain elementary properties of the lithosphere, hydrosphere, and atmosphere be represented together. Since the hydrosphere is the principal object of study, the functions of the lithosphere and atmosphere are of consequence only where they touch the hydrosphere. Thus it is sufficient to model in the coastlines and ocean bed, and to reproduce the surface winds over the ocean areas.

The original choice of the diameter and focal length of the paraboloid imposes limits on the scale and degree of similarity attainable. If the diameter of the basin is equal to four times the focal length, the rim makes an angle of 45° with the axis of rotation and limits the variation of the Coriolis parameter from 0.707 f at the rim to f at the vertex, or pole.

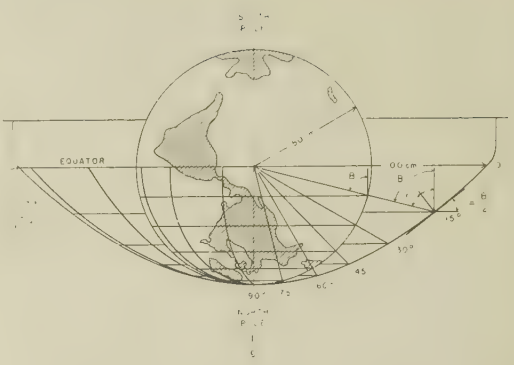

Fig. 2. Gnomic projection of the landmasses of the northern hemisphere on the interior of the paraboloidal basin. The variation of the Coriolis parameter at the equilibrium speed of rotation and the change of the combined gravitational and centrifugal accelerations are indicated.

The absolute magnitude of the Coriolis parameter is determined by the rate of rotation of the basin, which cannot (for practical reasons) depart from the equilibrium rate by more than a few per cent. This rate, in effect, also fixes the time scale of the model. For the Woods Hole basin, T_r is approximately 2.3×10^{-5}.

Despite the limitation that the Coriolis parameter cannot approach zero at the rim, the topography of the entire northern hemisphere has been projected on the interior of the paraboloid as an experiment, by the method shown in Figure 2. The projection was made gnomonically from the center of a sphere having a radius equal to the focal length of the paraboloid, placed so as to be tangent to the paraboloid at the vertex. The north pole of the sphere and the vertex of the paraboloid coincide. The resulting scale of the projection on the basin is the same as that of the sphere at the pole but increases toward the equator at the rim to $2\sqrt{2}$ times the north-south dimensions and 2 times the east-west dimensions of the sphere. This distortion is not objectionable to the eye.

Assuming that the length of a quadrant on the paraboloid is a characteristic length, the ratio L_r becomes 0.8×10^{-7} approximately, with respect to a quadrant on the earth. From this and the estimate of the time scale, T_r, the coefficient of lateral eddy diffusivity may be scaled by the ratio $(L_r)^2/T_r$, or 0.3×10^{-9}.

If a representative value for the lateral eddy diffusivity is in the order 10^8 cm²/sec. the scaled value for the basin becomes about 1 cm²/sec. which can be maintained experimentally.

The depth of water in the model may be exaggerated to allow for the nearly 100:1 inequality of the vertical and horizontal values of eddy diffusivity in the real ocean. If oceans are in the order of one thousand times wider than they are deep, an appropriate depth of water in the model is as much as one-tenth of the model ocean width. This can be accommodated, but departures from this ratio seem experimentally to produce very little effect.

Two other distortions exist in the paraboloid which are different from the situation on the earth; namely, the variation in the effective acceleration of gravity from g at the pole to $g\sqrt{2}$ at the rim, and the fact that at the equilibrium rate of rotation the depth of water measured normal to the free surface decreases as the cosine of the parabolic latitude. The increase of g and decrease of normal depth at the equilibrium rate of rotation cause the water to exert equal pressures on equal areas of the basin itself, but for the isobaric surfaces above the bottom to diverge poleward. This has an extraordinary effect which was explained by Dr C.-G. Rossby, that under these circumstances the cyclonic vorticity tendency associated with the horizontal convergence of the stretching water columns transferred from the rim to the pole is exactly equal and opposite to the anticyclonic vorticity tendency associated with the northward change in latitude. As a result, westward intensification of the circulation does not occur at the equilibrium rate of rotation. Having the effective planetary vorticity adjustment of the tendency under experimental control through meridional change in the depth of water in the model it becomes possible to study the changes in the broad pattern of the circulation under different combinations of the planetary, wind-stress and frictional vorticities. When the effective planetary vorticity tendency is increased by increasing the rate of rotation of the basin so that the normal depth at the rim is about 1.7 times that at the pole, the normal westward intensification of the circulation appears. If the rate of rotation is made correspondingly less than the equilibrium rate of rotation the sign of the planetary vorticity tendency is reversed, the circulation pattern is rotated 180°, so that the intensified circulation follows the eastern margins of the ocean basins. This occurs without any change in the intensity or distribution of wind torque. Theoretically the normal westward intensification should occur in the model when the depth normal to the free surface at the rim is $(1 + 1/\sqrt{2})$ times greater than that at the pole. The rate of rotation necessary to achieve the proper ratio of depths is, of course, a function of the average depth.

Figure 3 represents the experimental distribution of wind stress superimposed on that determined by Munk from average winds over the earth. The experimental curve approximates the natural one only in mid-latitudes. Experimentally the latitude of the inflection point seems to be more significant

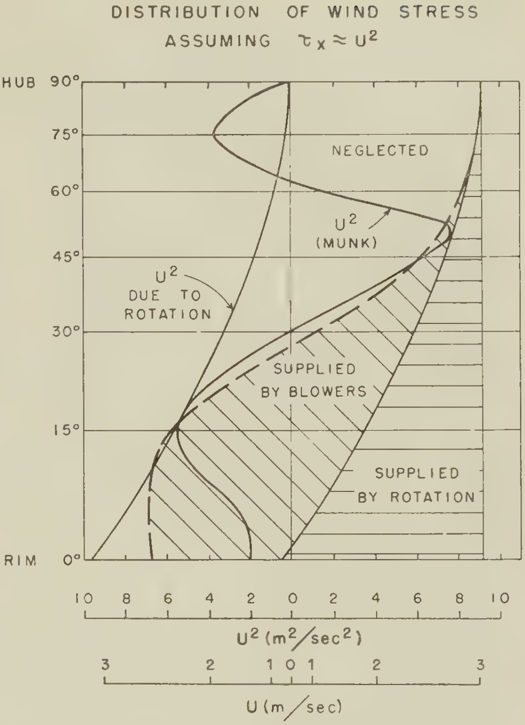

Fig. 3. Experimental distribution of zonal wind stress (dashed line) compared with that derived by MUNK (1950) (solid line) from records of the average zonal wind stress over the earth.

than the latitudes of the wind stress maxima, therefore attention has been concentrated on this adjustment for the time being. It is considered at the moment that a first approximation of the proper intensity of wind torque has been reached when the current velocities in the water approach the velocity scale L_r/T_r or 0.4×10^{-2}. The magnitude of the wind torque required to bring the velocity of the Gulf Stream nearly in scale is approximately 0.007 dyne/cm^2.

Because wavelets produce turbulent mixing at the coastlines, the wind stresses on the basin have been kept as small as possible. Wavelets, it is found, can be damped out to a great extent by covering the water surface with a film of Aerosol (a laboratory detergent). This film seems to have no important effect on the ratio of a given wind velocity to the water velocity produced. KEULEGAN (1951) reports similar results using Glim.

Modeling of the land masses has been done in commercial grade sponge rubber. This material permits the carving to be done originally on flat sheets which are easily bent to conform with the paraboloidal shape of the basin. The modeling was cemented in place. Besides being convenient to use, the sponge rubber modeling presents a rough surface along the margins of the ocean basins in contrast to the glassy smooth finish of the plastic of the basin which forms the bottom surface. The lateral roughness is of theoretical as well as experimental importance and can be changed through a wide range by either serrating the rubber, cutting it smoothly with sharp tools, or filling the pores with paint so as to be almost as smooth as the plastic surface of the basin. It is found that the roughness of the order of pore size in the rubber is of less consequence to the circulation than the large scale roughness of the geography of the continental masses themselves.

3. Some oceanographic results

The rotating basin experiments at Woods Hole have been in progress only a few months, so that this discussion is both qualitative and subject to change. It is regretted that no instantaneous photographs of the circulation, such as Figure 4 (opposite p. 318) can represent the changing occurrences that may be seen during an hour's operation of the basin. The description that follows has been written with the realization that others might have described or interpreted the same experimental results in other ways.

When the model is rotated at the optimum angular velocity for normal westward intensification, the circulation in both the North Atlantic and North Pacific compartments is dominated by a swift, narrow current flowing along the western margin of each compartment. The current in the North Atlantic compartment follows a course similar in many ways to present ideas of the course of the Gulf Stream. This current is composed of water from the south central North Atlantic area; from the slow drift of water upwelling in the lee of the West African bulge, and from the swift and relatively narrow Guiana current flowing northwestward along the northern coast of South America. Water from these sources flows through the Caribbean and through the Straits of Florida with very little transverse mixing. There is a pulsation of the flow through the Florida Straits which influences both the anticyclonic sweep of a small fraction of the flow into the eastern part of the Gulf of Mexico and the steadiness of the flow downstream as far as the Grand Banks. The similarity of this flow to the Gulf Stream extends to such details as the persistent anticyclonic bend over the Blake Plateau, and the oscillating cyclonic and anticyclonic curvature of flow east of Cape Henry. Meander structures of standing or slowly progressive (downstream) waves have occurred in the region between Cape Hatteras and the Grand Banks in recent experiments. These are similar to the actual meander structures that have been described by ISELIN and FUGLISTER (1948) and FUGLISTER and WORTHINGTON (1951) except that the wavelength is too long by a factor of about three.

FUGLISTER (1951) has also described some branches of the Gulf Stream system in the vicinity of the Grand Banks. Branching has been observed in the basin current in this region but the character of the circulation appears to be different. Multiple currents in the basin consist in stagnating streamers on the southeast side of the main current. A sudden discontinuity may occur in the flow which causes the active current to pass the older segment on the left. If the new thrust does not branch in the cyclonic circulation of the Labrador Sea it may penetrate northeastward as far as the coast of Norway before stagnating and being itself wedged aside by the next active thrust.

The circulations produced in the rotating basin resemble the ocean surface circulations best in the western regions of intense currents and sharply bounded water masses. In order to obtain a pattern of circulation along the eastern borders of the North Atlantic that resembles the patterns thought to exist, and for the North Atlantic Current to make its way toward the British Isles and to turn into the Arctic Ocean along the Norwegian coast, it is necessary in the model to vent the Arctic Ocean basin and return this discharge to the vicinity of the Gulf of Guinea. This artifice may be equivalent to the sinking of water in the northern North Atlantic, and the return, as either equivalent to upwelling off the coast of West Africa or possibly to the penetration of surface water northward across the equator from the South Atlantic Ocean.

The circulation of the North Pacific Ocean resembles some contemporary ideas of the actual circulation in several respects. In the model the Kuroshio is shorter than the Gulf Stream. It develops from the North Equatorial Current in the latitude of the Philippines north of Mindanao, accelerates steadily on its way past Formosa and the Ryikyu archipelago, is both swiftest and narrowest as it skirts the southern coast of Japan. During some experiments the Kuroshio stands off the southern coast of Japan, resembling to some extent the cyclonic bend described by UDA (1949), (1951). Beyond the 140° E meridian the Kuroshio decays rapidly, as does the Gulf Stream when it merges into the North Atlantic Current, and the circulation becomes quite sluggish. The equivalent of the Sargasso Sea in the Pacific is a very small patch of relatively motionless water directly south of the Kuroshio.

The prolongation of the Kuroshio Extension across the northern Pacific as the North Pacific Current is a slow, persistent movement which has no well defined boundaries but which accelerates slightly along the California coast and weakens again before joining the North Equatorial Current formed by the confluence of this water with the circulation northwestward along the west coast of Central America. The North Pacific Current crosses the mouth of the Gulf of Alaska and either contributes to, or sets up, a slow cyclonic circulation in the Gulf between Queen Charlotte Island and the beginning of the Aleutian archipelago. A similar cyclonic circulation appears east of the Kuril Islands, and a current flows southeastward along that chain which corresponds in a general way to the Oyashio. In certain experiments strong eddies develop in the region where the Kuroshio Extension and Oyashio meet off the coast of northern Japan, but in others the confluence is smooth or the Oyashio itself does not appear.

Within the main body of the North Pacific there is a slow general motion southward and southeastward from the paths of the strongest currents in the northwest which carries the complex filaments developed in the north toward the North Equatorial Current. The major contributions of water from the North Pacific to the North Equatorial Current appear to occur in the region between the coast of Central America and the 150° W meridian.

While the circulation within the North Pacific Ocean compartment is similar to that in the North Atlantic compartment, there are marked dissimilarities of detail. These may be due as much to the effects of northern seas on the Atlantic circulation as to the difference in shape and size of the two oceans in the temperate and equatorial latitudes.

4. In prospect

In none of the experiments with ocean compartments of realistic shape has it seemed desirable to include bottom topography other than that of the continental shelves to the level of the 200 meter isobath. Deeper topographic features such as major ridges and swells alter the circulation too much, and yet some modification of the otherwise featureless bottom seems to be needed. The surface circulation is thought to be represented in the basin and since, in nature, this is largely confined to the levels above the main thermocline, it may be that this interface is of importance to the wind-driven circulation. Experimentally a bottom surface having the topography of the main thermocline would influence the local changes in the planetary vorticity tendency and may alter the circulation pattern in instructive ways. In past experiments this has been considered as only a simple function of latitude.

Attempts to develop a density interface similar to that at the thermocline, through the solution of crystalline table salt dropped to the bottom of the basin, have failed. This failure is presumed to result from the halocline adjusting to an isobaric surface in which case the planetary vorticity tendency is canceled for motions in the upper less saline layer.

In homogeneous water, however, the Coriolis force is balanced only by the pressure gradient due to elevation of the free surface. Near the bottom, where velocities are small, the pressure gradient is greater than the Coriolis force. Therefore, there is marked anticyclonic motion in the bottom layer beneath the surface dome of the Sargasso Sea area. A line of weaker horizontal divergence extends northeastward from this point into the northern North Atlantic. There is a similar but weaker bottom circulation in the Pacific compartment. Presumably this mode of motion would not occur were it possible to establish a two layer system without losing experimental control of the planetary vorticity adjustment, except during periods of rapid acceleration due to increased wind torque. This problem and a study of the circulation resulting from equatorial heating and polar cooling in the absence of wind is of present interest, as are the circulation systems of the southern hemisphere.

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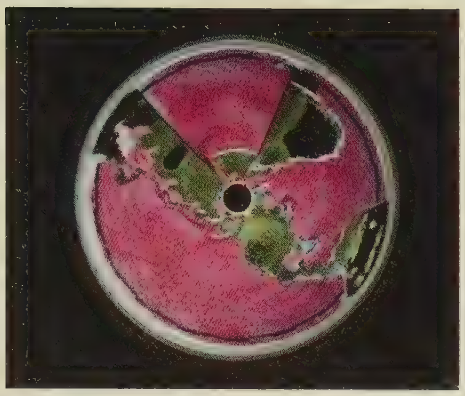
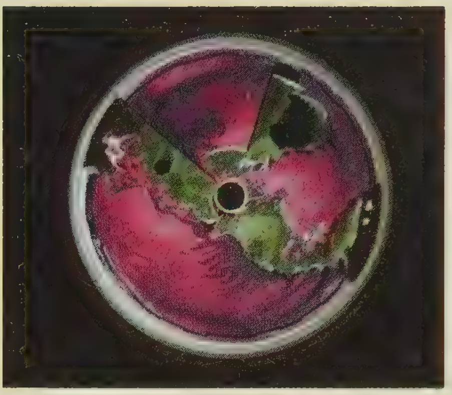
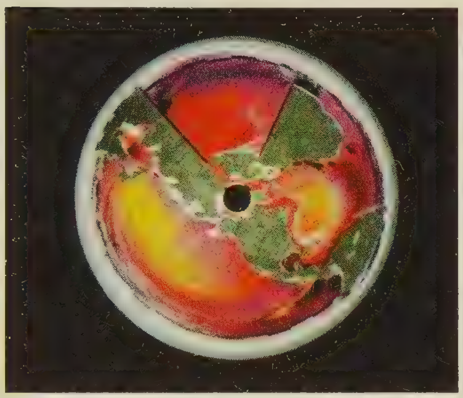


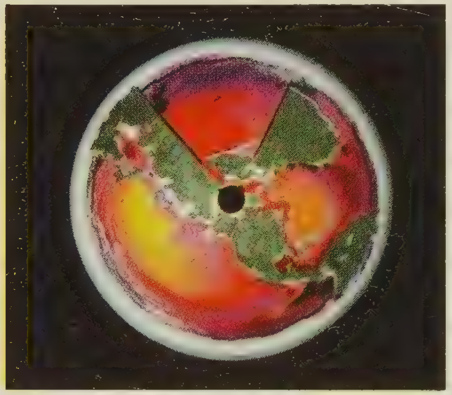
a) Color streamers from potassium permanganate crystals scattered on the bottom of the basin rotating at 3.18 radians/sec. Average depth of water 4 cm. Revolutions from start 24.



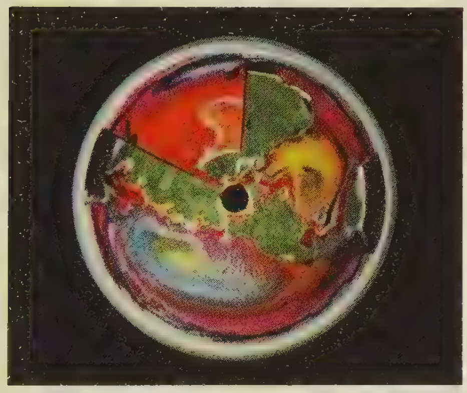
b) Same as (a) 150 revolutions from start. Color rises to the surface and occupies full depth of water in the regions of the coastal water masses.



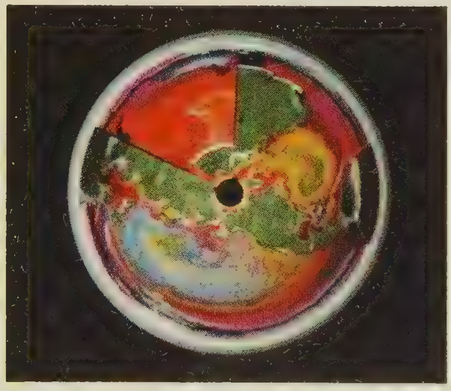
c) Occurence of patches of water on the right of the Gulf Stream system between Cape Hatteras and Grand Banks which may be similar to the patches of unusually warm water associated with the Gulf Stream.



d) An example of the type of multiple current in the Gulf Stream system in the vicinity of Grand Banks revealed in the basin. This differs from the description of the natural occurrence given by FUGLISTER (1951) and may not be the same phenomen.



e) Structure of the Gulf Stream and Kuroshio current systems 400 revolutions after the introduction of potassium permanganate crystals on the bottom and blue ink on the surface. The pulsating character of the flow of the Gulf Stream can be recognized, and the cyclonic bend of the Kuroshio described by UDA (1949), (1951) is suggested.



f) Further developments of the experiment shown in (e) at 450 revolutions. The small amount of lateral mixing along the course of the intensified western circulation is shown as well as the relative areas of the Sargasso Sea and its equivalent in the Pacific.

The quadrilateral compartment in the middle of Asia can be used as a control. The boundaries of this compartment are straight sided and uniformly smooth. In all of the photographs the Arctic ocean is permitted to drain through this compartment and reenter the North Atlantic circulation by way of the Gulf of Guinea.

Contribution No. 626

BREVIORA

Museum of Comparative Zoology

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ON THE NOMENCLATURE OF THE PACIFIC GRAY WHALE

By William E. Schevill[1]

The gray whale of the Pacific has until recently been called *Rhachianectes glaucus* (Cope). In 1937 van Deinse and Junge published an important paper of which the main part is a thorough comparative study of subfossil *Eschrichtius robustus* bones from the Netherlands, comprising one adult cranium and two juvenile crania, one of which was associated with the mandibles, scapulae, and other parts of the skeleton. These they compared with an adult *Rhachianectes glaucus* skeleton in the British Museum, as well as with the published material on both forms. Although the subfossil bones are naturally worn and fragmentary, as well as being for the most part juvenile, they present ample characters to indicate that they and the gray whale are congeneric. At this point I would like to emphasize that the following criticisms of van Deinse and Junge's conclusions are directed solely at their taxonomy; this involves no disparagement of their important and valuable osteological work, which has demonstrated the generic identity of *Eschrichtius* Gray 1864 and *Rhachianectes* Cope 1869 (= *Agaphelus* Cope 1868). But they also argue for specific identity, and thus unite *Rhachianectes glaucus* (Cope) 1868 with *Eschrichtius robustus* (Lilljeborg) 1861. Moreover, they argue that Dudley's scrag whale (1725), named *Balaena gibbosa* by Erxleben (1777, p. 610), is the same form, and therefore say (1937, p. 181), "After this it is clear that the name of this whale must be changed into *Eschrichtius gibbosus* (Erxleben). We must emphasize that with the bones we have now at hand we cannot give any argument that the Pacific and Atlantic representatives of *Eschrichtius* should be specifically different." But by the same token these bones cannot prove that these whales are specifically identical.

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[1] Contribution No. 626 of the Woods Hole Oceanographic Institution.

Additional and better material of *E. robustus* may present more specific characters, but until such material turns up, it seems unfortunate to take a well-grounded name of a well-characterized living form, known from complete specimens, and replace it with that of a form so imperfectly known from such incomplete material that specific characters cannot be entirely established; instead it seems better not to change the name of the well-known form.

It is even less desirable to use the name (*gibbosa* Erxleben) of a form which from the beginning has been an unrecognizable literary curiosity. Considering the available information, which is scanty though oft repeated, the most that can be said for *Balaena gibbosa* Erxleben is that it may be an *Eschrichtius*, but since it is not specifically well characterized and since nothing sufficiently like it has ever again been reported from anywhere near the type locality ("the Coast of New England") or elsewhere in the Atlantic, it seems to be stretching probability to submerge in it known forms from other regions. Detailed consideration of the uncertainties in attempting to identify Dudley's scrag whale (*Balaena gibbosa* Erxleben) are omitted here. From time to time cetologists have tried to identify this beast, but have always been frustrated by various irreconcilable data, the chief of which is perhaps the utter lack of specimens. Cope's attempt to embody *gibbosa* Erxleben was undermined by his confusion over a dilapidated specimen of *Balaenoptera acuto-rostrata*, so that he formally withdrew in 1884 (p. 1124). Although he did not publish details, it is probable that Cope used much the same reasoning as van Deinse and Junge in associating Dudley's scrag and the Pacific gray whale in the same genus. Thus it appears best to continue to use *robusta* Lilljeborg for the subfossil European form.

As to the nomenclature of the Pacific gray whale, it seems reasonable to retain the trivial name *glaucus* until better material of *Eschrichtius robustus* may demonstrate specific identity (although Cederlund (1939, p. 282) believes the holotype sufficient for this). It is therefore suggested that the living Pacific gray whale be called *Eschrichtius glaucus* (Cope).

This status may be summarized thus:

Genus
  Eschrichtius Gray 1864 (p. 350). Type species (by subsequent designation by Lilljeborg 1865, p. 494): *Balaenoptera robusta* Lilljeborg 1861.
Species
  Eschrichtius robustus (Lilljeborg)
    Balaenoptera robusta Lilljeborg 1861, p. 602.
    The Gräsö whale.
    Subfossil in northwestern Europe (English Channel to Baltic Sea).

Eschrichtius glaucus (Cope)
Agaphelus glaucus Cope 1868a, p. 160, 1868b, p. 225.
Rhachianectes glaucus Cope 1869, p. 15.
The California or Pacific gray whale; devilfish.
Recent in North Pacific Ocean (Baja California to Korea).

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Massachusetts Institute of Technology, pages 127-135, December, 1951

THE FLUSHING OF HARBORS AND OTHER HYDRODYNAMIC PROBLEMS IN COASTAL WATERS

BY

ALFRED C. REDFIELD

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Before the first World War, when the possibility of conflict between England and Russia was considered, it was said that a whale could not fight a bear. Modern global warfare has dispelled this illusion. Warfare must be carried into the enemy's territory, and this may be accomplished only by putting ashore and maintaining ground forces in full strength.

The coasts and their adjacent waters provide two critical zones which must be crossed. In the initial stage, landings must be made and beachheads established where best they may. Later, enemy ports may be captured and used for the continuous and heavy transport of men and materiel from ship to shore. At home, ports of embarkation must be maintained, with facilities for staging overseas traffic. Because these ports occupy fixed points established by accidents of geography, they are natural targets for the activities of the enemy. Moreover, they are the places where access to the sea has favored commercial and industrial development, populous places whose orderly life is essential to the strength of the nation.

Oceanography, which is in part an application of hydraulics to certain phenomena of the sea, paid little heed to the characteristics of coastal waters, until recently. Its principal preoccupation has been with the circulation of the deep sea where, uncomplicated by boundary phenomena, hydrodynamic computation permits the practical assessment of the movements of the water. Only in the case of the tides and the practical aspects of beach protection and harbor improvement were coastal phenomena intensively explored. Within the past ten years, the necessities of warfare, the need of biologists to understand the shoal water environment, and the increasing problem of disposal of pollutants have stimulated work on the waters along the coasts and in harbors.

Large-scale amphibious assault, which became a critical factor in the past war, brought into prominence the undeveloped state of knowledge of waves, swell, and surf. Landing places had to be selected where the state of the off-lying sea and the contour of the bottom made the operation of landing craft possible. Selection of the day and hour of attack required the development of forecasting, which depends upon tracing the sequence of events between the production of waves by winds, the transmission of the disturbed sea state, sometimes over great distances, by swell, and its final dissipation at the beach as surf. Knowledge of the tides was obviously critical, as proved by the disaster at Tarawa. Long shore currents, arising from tidal motion or the action of wind waves and surf, presented important problems in the navigation and handling of landing craft. They may also distort the refraction pattern of waves and swell on approaching the coast. The requirements have stimulated a great deal of observation and theoretical study, much of which has found its way into the published literature. [5]

Amphibious operations require the development of unusual types of vessels which present the naval architect with hydrodynamic problems not featured in the design of conventional craft. The design of some effective form of portable breakwater, capable of dissipating the organized motion of the waves and strong enough to withstand their action, is a pressing problem.

The protection of an amphibious task force while off the beach involves many problems in common with the protection of harbor mouths and of coastwise shipping. In shallow waters, the transmission of underwater sound is seriously affected by reflection and reverberation arising from the bottom and in degrees depending on its character. Accessions of fresh water from land drainage decrease the homogeneity of the water and thus exaggerate the difficulty of detecting approaching vessels by underwater sound.

Coastal defense employs a variety of contrivances, such as mines and nets, which are moored to the bottom. Such equipments are subject to the action of tidal currents, which may be strong in critical places. Design must take account of the drag to which the equipments are exposed, lest they be carried away or rendered in some way inoperative. The increased drag occasioned by the accumulation of fouling organisms exaggerates this problem. Other equipments are planted on the bottom, where they may sink and become buried in soft mud or may be rendered ineffective by the scouring action of currents across the bottom. To cope with these effects requires better knowledge of the relation between tidal motions and the process of sedimentation.

I mention these items to give some idea of the scope of the problems encountered in coastal waters. I propose to discuss in greater detail the problem of the flushing of harbors. While this matter obviously has some bearing on the active measures to be expected in wartime, such as radiological contamination, its importance is greater in connection with the preservation of the harborside as a place for civilian activities. The impetus for its study has come from civilian needs for the abatement of pollution and the maintenance of industrial, fisheries, and recreational values, rather than from military considerations. The increased construction of industrial plants on the waterfront in response to the military requirement has, however, accentuated these problems.

The primary question to be answered is, how rapidly is the water of a harbor renewed with sea water? A corollary is, how greatly will any given source of pollution accumulate in particular places? We may deal with the steady state resulting from more or less continuous pollution from industrial and domestic sources, or the transient condition which might follow some accident of warfare.

A harbor is usually a body of water sufficiently landlocked to be sheltered from the large waves raised by storms at sea and from the ocean swell. The natural or artificial barriers which protect the harbor from the open sea also protect it from the action of coastal currents, and harbor waters are relatively stagnant when compared with exposed coastal waters. These barriers act as selective wave filters and usually do not limit access of the long-period waves which constitute the tide. In fact, the amplitude of the tide is frequently augmented within a harbor as the result of reflection and resonance. So it is that the tides are the prime mover in the circulation of a harbor. In passing it should be said that certain types of embayment, such as those enclosed by barrier beaches, have inlets so small that the ocean tide is damped on entering. Where the basin has sufficient breadth, wind-driven currents rather than tides may provide the effective circulation.

Many harbors are situated at or in the mouth of rivers, the fresh waters of which give the hydrography distinctive characteristics which may be referred to as *estuarine*. The fresh water becomes mixed with salt water as it moves seaward, with the result that characteristic gradients of salinity occur along the length of the basin, and frequently between the surface and bottom. Other harbors, in dry regions where runoff is limited and evaporation exceeds precipitation, present conditions which are reversed, in that the net movement of water is inward and the waters become more saline as the head of the basin is approached. We propose the term *anti-estuarine* to designate this type of circulation. In both these cases the pattern of circulation is determined by the movement associated with the accession or loss of fresh water. An intermediate group of harbors receive additions of fresh water which are so limited that they do not affect the hydrography greatly. The circulation in such cases is predominantly tidal.

We will limit attention to the estuarine type of circulation, since it is most common and since the fresh water of the rivers may be used as a tracer in dealing with the flushing problem.

To generalize, an estuary consists of an enclosed basin, freely exposed to a limitless source of salt water at its mouth and receiving continuous accessions of fresh water at its inner end. The tides of the open sea enter the estuary as free waves and give rise to periodic oscillations of its water. Since tidal flow has turbulent character, mixing occurs along the length of the basin and an exchange of water between its parts and with the open sea is maintained. Superimposed on the tidal oscillation is the continuous discharge of river water at the head of the estuary. This gives rise to a gradient in level and pressure along the basin and results in a net drift of water seaward equal to the river discharge.

The problem is to explain the motions and the resulting distribution of salinity which arise from the combined effects of the oscillatory tidal flow and the continuous advective motion due to the accession of fresh water. Limiting the discussion to steady states accompanying periods of constant river flow, the two basic conditions are established that, during any tidal cycle:

1. There is a net seaward transport through every section across the basin of a volume of river water equal to the discharge of the river in that period of time. This transport is required to maintain constant volume.

2. There is no net exchange of salt through any section across the basin. This condition is required to maintain constant distribution of salinity. There are in addition a number of complicating conditions which must be taken into account.

The mixtures of fresh and salt water formed in the estuary are less dense than the source sea water and tend to occupy a layer at the surface. Estuarine waters consequently are often stratified with respect to salinity and this tendency increases with the relative depth of the basin, as seen in Fig. 1.

When stratification occurs, the transport of fresh water seaward is limited to the diluted upper layers. The fresh water molecules, however, cannot move seaward separately from the salt water with which they are mixed. Consequently, within the mixed layer the entire water mass acquires a net seaward motion. The volume of this drift exceeds the river discharge in proportion to the relative parts of sea water and fresh water in the mixture. In order to maintain continuity of volume and salt content within the basin, the undiluted sea water below the mixed layer must move up the basin at a compensating rate.

A two-way system of circulation is thus established in many estuaries. Although the motions are small compared with those due to tidal oscillation, the effect is shown repeatedly by current measurements in which the ebb exceeds the flood in surface waters, with the reverse obtaining at greater depths. [6,7,8] This phenomenon may create a powerful machine in which the tidal energy consumed in mixing is directed by the resulting distributions of density to produce greatly augmented advection. Thus, in the Strait of Juan de Fuca, tidal mixing in the channels of the San Juan Islands causes a net drift seaward in the surface layers of fifteen times the volume of water discharged by the tributary rivers, with a compensating flow of sea water landward in the deeper parts of the channel.

A second condition which influences the pattern of circulation and the resulting distribution of salinity arises from the rotation of the earth. It is well recognized that the Coriolis force results in an excess transport of water landward along the right side of a tidal basin during the flood and seaward along the left side during the ebb. The reference is to an observer in the northern hemisphere looking landward. In channels of sufficient width, this effect is frequently shown by a greater tidal range along the right bank. This phenomenon appears to explain the fact that in many estuaries the water on the right side is more saline than on the left, as the river discharge descends predominantly along the left side of the basin. The pattern of salinity distribution may be conceived of as the residual effect of the Coriolis force on the unequal motions of the tide during the flood and ebb, that is to say, on the net drift of the mixed water seaward and on the compensating landward drift of the sea water. It can develop only where the basin is broad enough to prevent the complete mixing of water in the horizontal plane, as seen in Fig. 2.

The three basic types of pattern of circulation and salinity which arise as the result of the relative predominance of the several conditions mentioned are diagrammed in Fig. 3. The variables which determine the pattern are the relative volume of the fresh water discharge, the intensity of the tidal mixing, and the dimensions of the basin. All conceivable intermediate conditions are to be expected, and in a single basin the typical pattern may vary from place to place as the result of geographical irregularities in form.

Several transient factors are also operative. River flow may vary greatly with the season, and thus distort the characteristic pattern. Warming of the surface water in summer will augment the tendency for stratification, particularly in deeper basins. Winds contribute to the rate of mixing and in broad basins with small tides may completely dominate the circulation.

At the present time, a number of oceanographers are seeking effective ways of analyzing the hydrodynamic phenomena of estuaries, not only to secure a more exact understanding of what is happening, but to find useful means of evaluating the rates at which estuarine waters are being exchanged with the sea.

The most elegant application of classical hydrodynamic principles to the problem has been made by Arons and Stommel. [1] Limiting consideration to a channel of uniform width and depth, open at one end to a source of water of constant salinity, receiving at the other end a constant accession of fresh water, and agitated by a tidal oscillation assumed adequate to produce complete mixing in the plane normal to the axis, they have arrived at a solution for the mean distribution of salinity along the axis. The procedure depends on equating the seaward advective movement of salt, which accompanies the escape of fresh water required for the conservation of mass, to the opposite movement of salt by eddy diffusivity required to maintain constant salinity distribution. Making suitable substitutions to provide for a coefficient of eddy diffusivity as an explicit function of tidal range and the dimensions of the basin, they deduce an exponential equation

$$\frac{S}{\sigma} = e^{F(1-1/\lambda)},$$

which gives the mean salinity of the water S, relative to the salinity of the source, σ, at each fraction of the length of the basin, λ, in terms of a constant F designated as the "flushing number." The flushing number is a function of the fresh water discharge D, the tidal amplitute ξ, angular frequency ω, the depth of the channel H, and its volume V. The relation of these factors is

$$F = \frac{DH^2}{2B\zeta_0^2\omega V} \; ,$$

where B is a proportionality factor.

The distribution of salinity along a uniform channel, as predicted by Arons and Stommel's equation for a range in values of the flushing number, is shown in Fig. 4. The figure is useful in showing how the salinity will change if any one of the factors on which the flushing number depends is varied. The curves correspond well enough with the observed salinity in selected narrow estuaries to suggest that the flushing number may serve usefully in classifying estuaries of the narrow type. Unfortunately, the values of the proportionality factor B obtained from the data on real estuaries vary by an order of magnitude in different cases, which means that the equation fails in evaluating the intensity of mixing from given parameters of the system. The restrictions imposed by the assumption of uniform dimensions prohibits the application of this treatment to the many basins of irregular morphology found in nature.

The attempt of Arons and Stommel to apply the physics of continua to the description of estuarine circulation was stimulated by the success of Ketchum [2, 3] in developing an empirical method of analysis based on the fundamental idea that the element of mixing volume is defined by the length of the tidal excursion. Ketchum started from an examination of the tidal prism concept sometimes employed by sanitary engineers in estimating the ability of natural waters to dilute continued additions of sewage. It is assumed that the volume of water which enters and leaves a basin with the rise and fall of the tide is available to dilute the increment of pollution added to it during each tidal cycle. Ketchum points out that this assumption could only lead to correct estimates if the water in the basin were completely mixed and if none of the water which escaped during the ebb returned on the following flood tide. Since these conditions are not met generally, the tidal prism concept gives an exaggerated estimate of the rate of flushing.

Ketchum's procedure starts from the consideration that the greatest distance over which mixing can be complete during a single tidal cycle is the mean length of the excursion of water on the rising tide. He consequently divides the basin into a series of segments of such length and examines the exchanges between them required to maintain the steady-state conditions. Segmentation is accomplished by spacing the boundaries so that the high tide volume of each segment is equal to the volume of water which crosses its seaward boundary on the rising tide to create the tidal prism of the enclosed basin. The innermost segment is defined so that its intertidal volume is equal to the volume of river flow during the tidal cycle. The river flow thus determines the dimensions of the other segments and enters into the estimations. The procedure is diagrammed in Fig. 5.

Simple algebraic considerations lead to the following definitions of the properties of each segment.

1. The exchange coefficient γ_n, expressing the fraction of the contained river water which moves from any segment seaward during each tidal cycle is given by

$$\gamma_n = \frac{P_n}{P_n + V_n} \; ,$$

where P_n is the intertidal volume of segment n and V_n is the low tide volume of this segment.

2. The total volume of river water accumulated under steady-state conditions in any segment. Q_n is given by

$$Q_n = \frac{R}{\gamma_n} \; ,$$

where R is the river flow per tidal cycle. This expression determines the mean salinity of each segment and the fraction of fresh water within it, F.

$$F = \frac{Q_n}{P_n + V_n} \; .$$

3. The volume of water which escapes from any segment and does not return on the following tide is given by the ratio R/F. This is the property useful to the sanitary engineer.

4. The mean age of the water present as the result of accumulation during all the tidal cycles which have led up to the steady state is given by the reciprocal of the exchange ratio, or $1/\gamma_n$.

By suitable summation, the properties of the entire estuary may be obtained from those of its constituent segments.

Ketchum's procedure has been checked by observations on the distribution of salinity in Raritan River and Raritan Bay. The segmentation of the basin is shown in Fig. 6. The observed and calculated average salinity and the fraction of river water present in various segments along its length are shown in Fig. 7. The agreement is excellent.

The final success of the procedure has been in analyzing the observed distribution of coliform bacteria along the estuary of the Raritan River. These organisms enter as pollutants with the river water Their numbers diminish in the estuary as the result of three processes, (1) dilution of river water by sea water, (2) mortality due to predation by planktonic animals, and (3) mortality following exposure to lethal factors in sea water.

The effect of dilution is a simple function of salinity and is readily estimated. The other two factors, however, depend on exponential functions of time of exposure. Since the method of analysis includes means of estimating the age of the fresh water in each segment, it has been possible to develop an equation from which the joint effects of dilution, predation, and bactericidal action can be calculated. [4] Table 1 shows the results of this estimation, using constants obtained from laboratory experiments. It indicates the relatively great importance of the mortality factors as compared with dilution. Observation showed that a concentration of coliform bacteria of 115,000 cells per milliliter at the head of the estuary was reduced to 130 at the river mouth. Calculation indicated that the reduction should be to 350 cells in this distance. This is a most satisfactory agreement, in view of the empirical nature of the treatment and the character of the basic data.

Table 1

Number of Coliform Bacteria in Raritan River Water at Low Tide
(cells per milliliter)

	Predicted as result of		
Segment	Dilution alone	Dilution mortality and predation	Observed
1	115,000	86,000	115,000
2	110,000	70,000	--
3	98,000	51,000	--
4	84,000	26,000	--
5	63,250	8,400	--
6	40,200	2,900	--
7	24,200	1,020	--
8	17,200	350	130

The great virtue of Ketchum's treatment is that results are obtained directly from information on the dimensions of the basin, the tidal range, and the river flow, data which are frequently available from charts, tide tables, and hydrological sources. Special oceanographic surveys are not required, and the variable shape of the basin is taken into account. The theory assumes complete mixing, however, within the length of the tidal excursion, and this limitation requires examination.

From theoretical considerations, Ketchum has shown:

1. If horizontal mixing along the axis of the tidal excursion is incomplete, estimates of the exchange ratio will be too great, estimates of the accumulation of river water too small. This effect is to be expected where the turbulent character of tidal flow is reduced.

2. If horizontal mixing is incomplete across the channel, the estimates of the exchange ratio and of the total accumulation for the segments as a whole is unaffected theoretically. This consideration accounts for the successful application of the treatment to Raritan Bay, where observation shows that the salinity is not uniform across the basin.

3. If vertical mixing is incomplete, as evidenced by vertical stratification of salinity, estimates of the exchange ratio will be too small, and of the accumulation of river water too great.

Ketchum has suggested that in the latter case satisfactory estimates can be obtained by considering the depth of the estuary to be limited to the greatest depth at which mixed water may be detected, as though the water below the mixed zone had no part in the tidal mixing process and could be replaced, without changing the distribution, by a false bottom.

The distinction between the shallow estuary in which the water is well mixed to the bottom and the deep estuary where the escaping fresh water is limited to a shallow mixed layer above a deeper mass of invading sea water is fundamental. The former lends itself to theoretical analyses, such as those of Arons and Stommel and Ketchum, because of the simplifications resulting from the assumption of complete mixing. The latter, however, has advantages from the point of view of observation, since the outflowing mixed layer and the inflowing countercurrent are separated and it is possible to examine the mixing at the horizontal interface which separates them.

The properties of a deep, fjord-type estuary situated on the west coast of Vancouver Island, known as Alberni Inlet, have been thoroughly examined by Tully. [9] In this estuary the mixed layer in which river water escapes is concentrated within a depth of ten to fifteen feet at the surface. Below this is a middle zone which is evidently exchanging water with the upper layer. At depths greater than thirty feet, the sea water appears to be uncontaminated with the river discharge. From direct consideration of the distribution of salinity accompanying various volumes of river flow, estimates have been made of the exchange coefficient characterizing various parts of the channel and the resulting volume and velocity of the nontidal drift of the mixed water seaward. A striking result which appears is that as the mixed water progresses seaward its volume is increased from the admixture of sea water from below. This does not result in a deepening of the mixed zone, as might at first be expected, but rather in an acceleration in its movement toward the sea. This may amount to a three- or fourfold increase in velocity in a distance of twenty miles. This is an interesting observation for theoretical analysis.

Another problem is to explain the depth to which the mixed water extends. With increased river flows the depth of the diluted layer does not increase, but actually decreases up to a point, beyond which it increases again as maximal river flows are approached. A phenomenon which appears to depend on a similar balance of forces occurs in the mouths of rivers which enter directly into the sea. In such cases, salt water intrudes as a wedge under the effluent river water. The movement of such saline wedges with varied tidal flow and river discharge has attracted the attention of engineers because of its influence on industrial and domestic water supplies. [8]

A baffling and intriguing feature in the study of estuaries is the fact that the character of the problem changes with the geography of the basin. Different methods of observation and analysis are required in different systems. Chesapeake Bay, for example, is relatively shallow, yet a distinct salinity gradient is present and differential velocities mark the flow of the deep and superficial water. The analysis cannot assume that mixing is complete, nor that the deep water is an unmixed countercurrent of pure sea water. Pritchard has suggested a different attack on the circulation in this estuary. [7]

Pritchard's proposal is to develop techniques for computing the character of the circulation from the distribution of pressure associated with the distribution of mass within the basin. This is the classical method of dynamic oceanography. The application of this method requires the establishment of some reference level in order to describe the field of mass. In the open ocean, this is taken as some great depth at which motion may be assumed to be absent. In such an estuary as the Chesapeake estimates of the nontidal drift from direct current observations indicate that in the deeper layers the pressure gradient must be landward, while in the superficial layers it is seaward. Between these zones must lie a layer of no motion, which may serve as a reference level for dynamic computation. Whether this level can be practically identified, and whether the complications arising from the presence of boundaries, the effect of friction and acceleration, commonly neglected in open ocean studies, can be dealt with so as to produce a useful tool for analyzing the behavior of estuaries, remains to be seen.

A final method of examining the circulation of estuaries is the use of scaled hydraulic models. These may be *synoptic models* which replicate in detail the form of real basins and the several factors to which their water is exposed, or *analytical models* in which given parameters of some aspect of estuarine behavior are reproduced under controlled conditions to serve in the development and test of theory.

The synoptic model has the great advantage that it permits an examination of basins whose geographical form is too complex for analysis by rational methods, and that it allows the study of external factors such as the winds. The shortened time scale favors the study of transient events such as occasional contamination or the results of cyclic changes in climate. Owing to the difficuties and imperfections of scaling, the behavior of the model must be controlled by careful comparison with the prototype, and its operation adjusted until the conditions at critical points are satisfactorily reproduced. When this is done, the model may be useful in drawing attention to places where specially interesting events take place, as well as giving a synoptic picture of the system as a whole.

The difficulties in constructing scaled replicas of real estuaries arise from the great distortion in depth frequently required in models of practical dimensions, and from the difficulty of reproducing correctly the roughness factor of the bottom and the intensity of the mixing process.

In models of deep estuaries, the distortion need not be too great to permit Froude scaling to be applied with satisfactory results, as was done by Tully in a model study of Alberni Inlet. [9] In shallow models, the influence of surface tension cannot be neglected unless the fluid is at least 7 millimeters deep. As a result, it is impossible to replicate the behavior of very shallow water in models of reasonable dimensions without introducing undesirable distortion of the depth scale.

The special feature which distinguishes the estuary from the systems reproduced in the more usual hydraulic models, is the mixing of fresh and salt water. In models scaled according to Froude, turbulence is too small in relation to the other features. As a result, mixing is deficient and the fresher water tends to flow out as a separate layer over the surface. This difficulty can be satisfactorily overcome by reducing the ratio of the densities of the mixing fluids in proportion to the vertical distortion of the model. This adjustment improves the mixing effect due to natural turbulent processes, including that caused by the wind. The greatest need for improving the application of model techniques to the study of estuaries is to reconcile theoretically the several presently empirical scaling parameters having to do with mixing due to turbulence and wind stress. See von Arx [10].

While synoptic models of estuaries promise to have great value, particularly in relation to practical problems of the pollution of harbors, theoretical advances are to be looked for from analytical models employed in examining the basic phenomena of the circulation. Of major interest are the processes which take place in the interface between layers of fresh and salt water when subject to the stress of differential motion — as in the case of deep estuaries. A flume for the experimental study of such processes has recently been constructed at the Woods Hole Oceanographic Institution by Mr. Harlow Farmer, a graduate of this Hydrodynamics Laboratory. We hope that by this means our understanding of the natural phenomena of coastal waters will benefit from the practical and theoretical skills which are being developed here.

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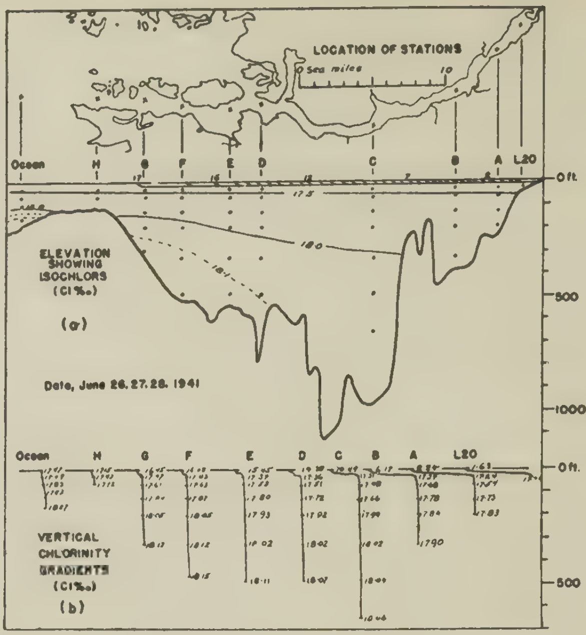

Figure 1. Vertical stratification of chlorinity in Alberni Inlet. A typical deep estuary. From Tully [9].

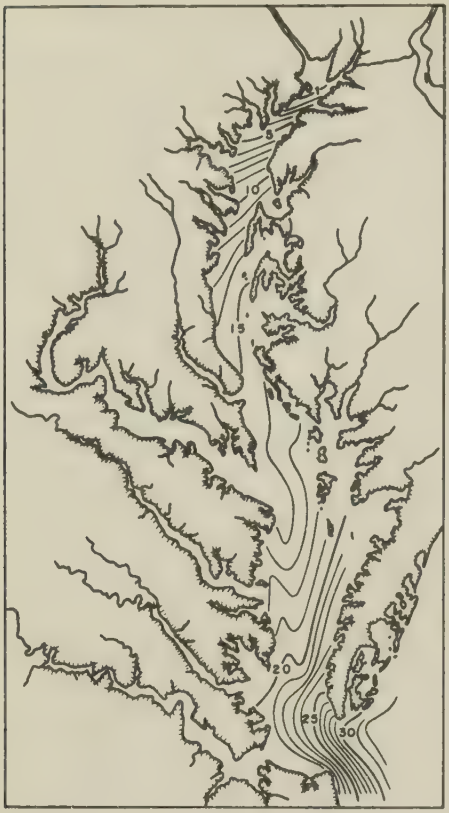

Figure 2. Horizontal distortion of salinity gradient in surface water of Chesapeake Bay. After Pritchard [7].

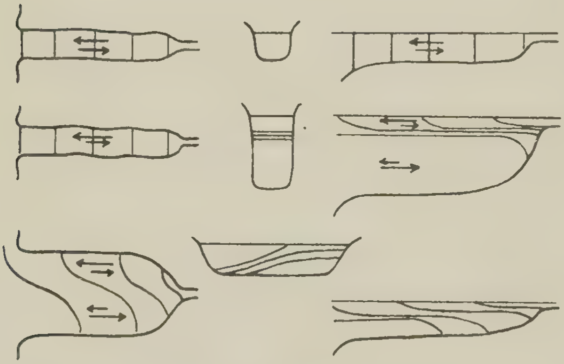

Figure 3. Three basic types of estuarine circulation showing the distribution of isohaline and the relative strength of the flood and ebb tidal currents:

Above: A narrow estuary with complete vertical mixing normal to the axis.

Center: A deep estuary with vertical stratification.

Below: A wide estuary with asymmetrical circulation due to earth's rotation.

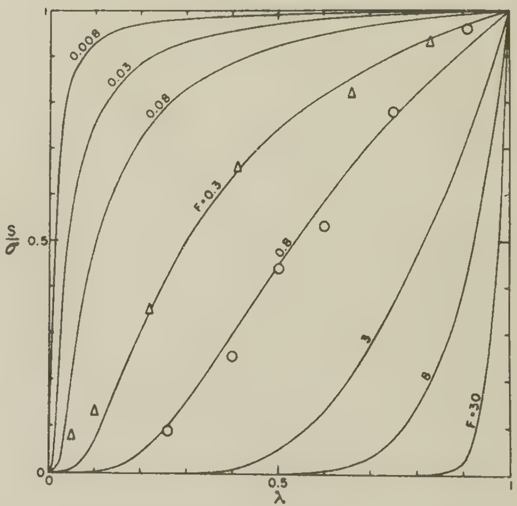

Figure 4. Theoretical distribution of salinity, S/σ, along a uniform channel of length λ. The points represent observed values for Raritan River (circles) and for Alberni Inlet (triangles). From Arons and Stommel [1].

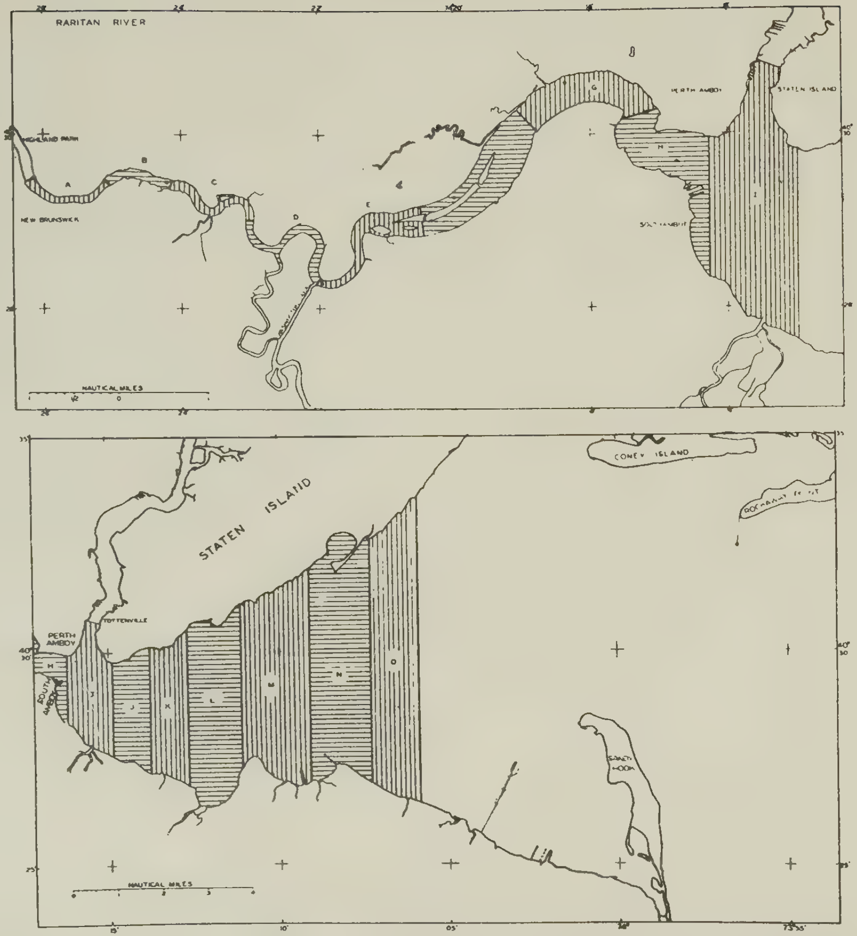
RARITAN RIVER
HIGHLAND PARK
NEW BRUNSWICK
PERTH AMBOY
STATEN ISLAND
SOUTH AMBOY
NAUTICAL MILES
A
B
C
D
E
G
H
I
STATEN ISLAND
CONEY ISLAND
TOTTENVILLE
PERTH AMBOY
SOUTH AMBOY
SANDY HOOK
J
K
L
M
N
O
NAUTICAL MILES

Figure 6. Raritan River and Raritan Bay, showing method of segmentation. From Ketchum [2].

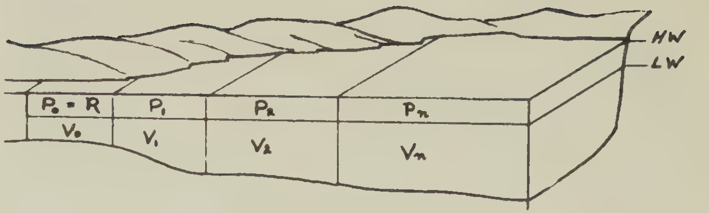
HW
LW
$P_0 = R$
P_1
P_2
P_n
V_0
V_1
V_2
V_n

Figure 5. Method of segmenting an estuary. $V_0, V_1, V_2, \ldots V_n$ are the low tide volumes and $P_0, P_1, P_2 \ldots P_n$ are the intertidal volumes of successive segments.

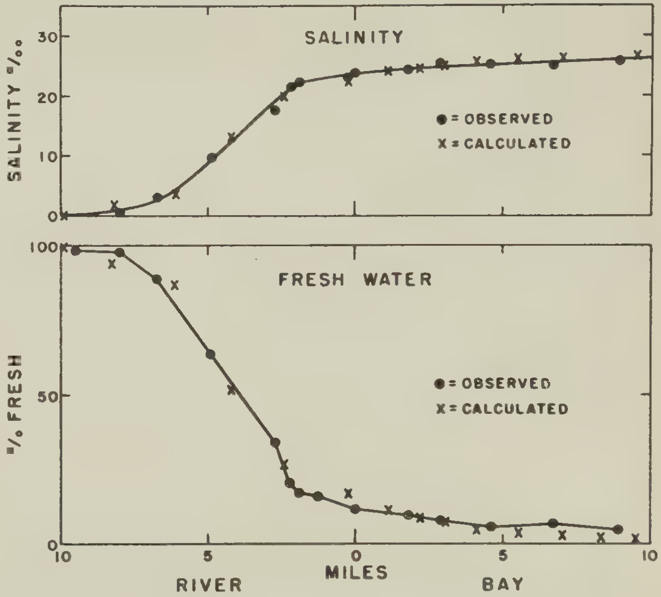

Figure 7. Comparison of the observed and calculated distribution of salinity and of fresh water in Raritan River and Raritan Bay in December 1948. From Ketchum [3].

Report of the year 1952

THE
WOODS HOLE OCEANOGRAPHIC INSTITUTION

REPORT FOR THE YEAR
1952

1953

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LOUIS W. HUTCHINS, Director, Bermuda Biological Station for Research, Inc.; Marine Biologist.

BOSTWICK H. KETCHUM, Marine Microbiologist.

JOANNE S. MALKUS, Meteorologist.

WILLEM V. R. MALKUS, Physical Oceanographer.

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Per F. Scholander, Physiologist.

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Mary Sears, Planktonologist.

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Floyd M. Soule, Principal Senior Oceanographer, U. S. Coast Guard; Associate in Physical Oceanography.

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IV. DIRECTOR'S REPORT

Introduction

During the year 1952 the Institution operated pretty close to peace time capacity on many interesting projects, the results of which should add measurably to the accumulation of oceanographic knowledge. More research could have been undertaken with little or no recruitment of additional administrative personnel, but the physical working space of the laboratory, and the operational capabilities of the floating units, were strained about to their limits.

If one were to ask what was the outstanding scientific contribution, or discovery emanating from the research staff of the Institution during the year 1952, it would be difficult, and unfair, to select one over another from amongst a half dozen or more noteworthy achievements.

The year will undoubtedly record from among the list of firsts, the following:

(*a*) Trawling far out on the continental slope where some species of fish new to science were caught; and the attending physiological studies carried out on the blood chemistry of deep-living fish.

(*b*) Field studies of the Northern Equatorial Current, and the improved exposition of these waters by their chemical and biological indices.

(*c*) Operation of an airplane in oceanographic-meteorological work, and the development of techniques and special recording instruments.

(*d*) A new conception of the Gulf Stream's flow-pattern as derived from laboratory models and field observations.

(*e*) Expedition Ski-Jump II to the North Polar Sea and the basic question of circulation which the data raise.

(*f*) The correlation of the number and size of sea-salt particles in clear air beneath clouds, with the number of cloud droplets within the clouds, and with the number and salt content of rain drops falling from these clouds.

(*g*) A theory was developed that relates the electric potentials in and about an ocean current in simple fashion to the total fluid transport.

The research program of 1952 in both military and basic oceanography received major support from the U. S. Navy Department's Bureau of Ships, Office of Naval Research, and Bureau of Aeronautics. The State of Massachusetts contributed materially to the shell-fishery investigations. To these several sources due acknowledgment is made.

A noteworthy innovation marked the first visit of the Institution's

Scientific Advisory Committee, when during March it spent three days looking over the laboratory organization; the research program; and interviewing members of the staff.

The activities of the year, and other items of note, are to be found under the headings: Scientific Program, Personnel, Vessels, and Plant. First let us examine the report of scientific accomplishment of which Drs. Iselin and Redfield have prepared a very interesting joint account.

Scientific Program

During 1952 the major effort at sea consisted of two long cruises, criss-crossing the trade wind latitudes of the North Atlantic. During the winter months the ATLANTIS and the ALBATROSS III worked together, while during the summer the former cruised in company with the tug KEVIN MORAN which had been chartered by Columbia University. In the course of these two cruises the ATLANTIS sailed approximately 27,000 miles and thereby secured many temperature and salinity observations from the tropical Atlantic which had previously only been crossed by a few individual profiles. It can now be said that so far as the North Atlantic is concerned the reconnaissance phase has been concluded. Few sizable areas remain that are devoid of temperature and salinity observations.

To summarize all available temperature data, Mr. Fuglister has begun work on a chart of the average temperature at 200 meters. Such a chart was published in 1936 in the Atlas Volume of the METEOR reports. There were then roughly 3000 stations available. It will be interesting to see whether any important differences appear on the new chart which will combine more than 60,000 individual observations.

While these two cruises were exceedingly long for our vessels, and many difficulties and much discomfort had to be overcome, they mark both the end of a long term plan and the beginning of a new one. Having established a reasonably reliable picture of the average current system over the whole North Atlantic basin, we can now turn our main attention to studies of departures from this mean pattern in more limited areas. In short, it is believed that physical oceanography is now ready to take up synoptic problems, and both the development of instruments and the planning of new surveys are being shaped accordingly.

An original objective of the winter cruise was to learn whether or not the current system near the Equator has some of the newly discovered characteristics of the Gulf Stream System. In an area where the currents are gaining energy from the winds are they sometimes narrow and streaky, and do they meander, as is the case farther north? Because of the lack of Loran navigation in the area, the relative weakness of the currents encountered, their lack of marked thermal structure and the long distances between ports, only marginal success was achieved on these phases of the program. On the other hand, the chemical and biological program, which was at first considered a secondary objective, turned out to be highly productive. The equatorial current originates in the regions of upwelling along the African coast, where the surface waters are greatly enriched with plant nutrients and are the site of intense biological activity. It was possible to trace the movement of this water by means of its biological and chemical characteristics across the Atlantic to within a few hundred miles of the South American coast. Dr. B. H. Ketchum in ATLANTIS and Dr. F. A. Richards in ALBATROSS III deserve great credit for the success of the chemical program. In addition, of course, a large number of temperature observations and soundings were secured from an area where data are old or entirely lacking. The reversing thermometer and the water bottle still seem to be the best approach in areas where we have only a vague understanding of the pattern of the relatively swift and shallow currents.

After the winter work in the trade wind latitudes, the vessels were turned over to Dr. W. M. Ewing in mid-April at Trinidad for the homeward voyage. The plan was to explore the deep geology of the Caribbean and the Gulf of Mexico. However, because of breakdowns and delays, most of his productive observational program lay between Cuba and Bermuda.

As already stated, during the summer the ATLANTIS assisted in a geophysical and geological survey of the trade wind area in cooperation with Dr. W. M. Ewing's group from the Lamont Geological Observatory. At the same time we supplied a team of hydrographic observers who secured temperature and salinity data as opportunity offered. As a result, for the first time we now have a reasonably complete picture of these factors from the summer season in the tropical Atlantic. Previously the distances to be sailed in outflanking the hurricanes had not seemed worth the effort.

In September the ATLANTIS parted company with the KEVIN MORAN and headed south for Rio de Janeiro. This was her first major excursion into the South Atlantic. The return voyage, which lasted until the middle of December with Mr. F. C. Fuglister in charge, was devoted to a study of the currents along the western margin of the Atlantic from the latitude of Rio to that of the Bahamas. While in South Atlantic waters the observational program indeed posed many more problems than were advanced.

The theoretical studies of Mr. H. M. Stommel and Dr. W. H. Munk have led us to expect that along the western shores of each ocean narrow, swift currents, comparable to the Gulf Stream, are to be expected. The fact, however, that the METEOR survey of the South Atlantic failed to put the Brazil Current in the class with the Japan Current, or the Gulf Stream, could be excused on the grounds that the METEOR stations were too widely spaced to depict a narrow and perhaps widely meandering current along the coast of Brazil. After all, what would we know about the Gulf Stream if we only had a dozen deep temperature stations between the whole of the U. S. coast and Bermuda? Thus on leaving Rio in October the ATLANTIS headed south-eastward, confidently expecting to encounter a marked temperature change that could be identified as the inshore edge of the Brazil Current. It is possible that this section was abandoned too soon, but also on subsequent sections further north nothing comparable to the Gulf Stream was encountered in South Atlantic waters.

Northwestward of the bulge of Brazil the sections were planned to show up another phenomenon predicted by theory. As the Guiana Current crosses the Equator the main thermocline layer should roll over as the direction of the effect of the earth's rotation changes from left to right. This too did not materialize in any obvious or simple manner.

It is probable that the observational program attempted from the ATLANTIS on her return voyage from Rio was entirely too ambitious, but it is also possible that in the North Atlantic we have been studying rather special circumstances of oceanic circulation. In any case, the hope has received a setback that if we knew the surface currents in one ocean rather thoroughly, we could predict the sub-surface thermal patterns in the other oceans.

The net result of the 1952 cruises in equatorial waters, therefore, is that our new observational techniques, which have been so successful from Cape Hatteras northeastward, cannot be immediately applied to other areas. In all probability in enlarging our field of study we must be patient enough to first go through a slow, painful exploratory phase.

Although we have neglected the Gulf Stream during the past year in our field program, there has been much thought and discussion about it in the laboratory. Based largely on the ALBATROSS III observations of the summer of 1951, Mr. F. C. Fuglister has come forward with a new hypothesis as to the best interpretation of the accumulated data. This was published in *Tellus*. His basic idea is that narrow, overlapping streaks of flow, separated by countercurrents, are more common than eddies along the inshore edge of the primary Gulf Stream.

The Gulf Stream studies were reviewed in May at a symposium in Washington, D. C., sponsored by the American Geophysical Union. This was well attended and our ideas were well received. Nine papers were presented. Perhaps the most provocative result of this symposium was that Dr. William L. Ford of Canada pointed out that in our recent Gulf Stream studies we have been neglecting to take into account the small amount of very fresh and cold water that is sometimes encountered at about 100 meters depth at the inshore edge of the current. This imposes a serious difficulty to Mr. Fuglister's hypothesis, unless it is found that this is easterly moving coastal water that has become entrained in the Gulf Stream in the Cape Hatteras area.

Mr. W. S. von Arx's efforts to reproduce the Gulf Stream System in his rotating basin are meeting with increased success, especially following a visit of Dr. C.-G. Rossby in February. He has completed a manuscript of a preliminary paper describing the results of these model studies.

Strangely enough, the deep temperature and salinity observations made during the last two winters by Messrs. Holmes, Metcalf, and Worthington in the Arctic Ocean are likely to play a considerable part in our thinking about North Atlantic circulation during the next few years. Their stations indicate that quite deep currents exist under the ice, having a transport as great as one-twentieth of the Gulf Stream. These currents clearly must derive their energy from differences in density, rather than from the winds. Thus, just as most investigators had come to the conclusion that the winds are all important, the whole basic question has been opened up again of how much of the energy of the North Atlantic current system comes from the winds and how much from regional density differences maintained by the climate.

During the summer, three new approaches to Gulf Stream problems were attempted. A brief visit of Mr. M. S. Longuet-Higgins of Cambridge University in 1951 stimulated Dr. W. V. R. Malkus and Mr. M. E. Stern to make a new theoretical attack on the character of the induced electrical fields associated with the Gulf Stream's flow. This led to the conclusion that the electrical potential across the Florida Straits would vary with the total transport. In July Mr. G. Wertheim installed electrodes at the terminals of the telephone cables across the Florida Straits, and permission has been granted for daily use of several of the telephone circuits for these measurements. Mr. Paul Smith, who has joined the staff of the Marine Laboratory of the University of Miami, will take over these measurements once the value of this approach has been demonstrated. Here, we hope is an independent method of evaluating the tide gauge observations as a means of measuring long period fluctuations in the flow through the Florida Straits. Thus, we may be able to prove out the value of old data, as well as to introduce a potentially more sensitive new method.

Late in July, using the CARYN and the BEAR, Dr. E. E. Watson and Dr. W. V. R. Malkus compared two different methods of observing the change of velocity with depth across the Gulf Stream. Both methods require a slow but steady motion of the vessel relative to the deep motionless water. Dr.

Watson used a propeller type current meter, while Dr. Malkus towed his new bathypitometer. It is lack of direct observation on the typical velocity profile of the Gulf Stream that makes it difficult to interpret the great mass of G. E. K. records that have been collected in recent years. Mr. W. S. von Arx has completed a paper summarizing this particular problem, which for the time being is making it most difficult to assign reliable values to the towed electrode results.

Finally, a beginning has been made in observing the Gulf Stream from the air. This new approach to Gulf Stream problems grew out of studies of infra-red radiation coming from the sea surface which Mr. H. Stommel has been making. Having become familiar with infra-red detecting devices and some of their limitations, he, and Mr. D. Parson, Jr. saw the possibility of building a radiation detector that would at least roughly indicate sea surface temperature from a low flying plane. Mr. Parson's brilliant adaptation of a standard Golay infra-red detector has resulted in a simple and remarkably versatile device which when flown at an altitude of about 1000 feet is usually able to give the sea surface temperature to within 2°F. Several flights along the inshore edge of the Gulf Stream south of New England have produced most promising results. Once an adequate navigational procedure has evolved it is evident that the changes in the large scale meander patterns can be surveyed on a week to week basis.

Dr. W. S. Richardson, who joined our staff in the Fall, hopes to improve the instrumentation and to take up a general study of the physical chemistry of the sea surface.

The arrival of a PBY airplane in April, on loan from the Navy, not only has permitted wide-spread surveys of sea surface conditions with the new infra-red device, but also made it possible for our group working in marine meteorology to take their observational techniques well out from the land. During June, Mr. A. F. Bunker, Dr. J. S. Malkus, Mr. K. G. McCasland and Mr. C. F. Ronne carried out a highly successful study of trade wind clouds off Puerto Rico. In November a successful flight observed the changes in a cold dry air mass as it moved out across the Atlantic seaboard to Bermuda. The long, patient instrumental development which Mr. McCasland has been mainly responsible for, paid off in a spectacular manner. Not one of the many flights was wasted through instrumental failure.

Mr. A. H. Woodcock and Mr. D. C. Blanchard also have accomplished a great deal of flying in the Hawaiian Islands area in connection with sea-salt nuclei studies. Their observations, in cooperation with meteorologists working for the agricultural laboratories at Hawaii, were completed in July, when Mr. Woodcock went on to Australia to make a series of measurements there on the effects of the marine environment on rainfall. He returned to Woods Hole in September with material for three important papers.

The emphasis in underwater acoustics during the year was largely on improvements in instrumentation, and on the study and interpretation of accumulated data. However, during the summer, Dr. J. B. Hersey set up an ambitious, new field program, using the CARYN and the BEAR on weekly trips out of Woods Hole. This work continues at year end.

Dr. C. B. Officer, Jr., who joined our group after completing his studies at Columbia, specialized on long range transmission phenomena.

An expedition to Bermuda in the CARYN early in the spring, supplementing a previous one to the San Diego area, added greatly to our knowledge of the acoustical characteristics of whales, both as acoustical targets and as noise makers. Mr. W. E. Schevill is particularly interested in these phenomena.

Beginning in the autumn, Dr. R. H. Backus, a marine biologist, who completed his formal training at Cornell, joined Dr. Hersey's group to devote himself to the echo characteristics of schools of fish, and this at long last appears to be a favorable opportunity to tie together fisheries biology and modern underwater acoustics.

Exploratory fishing was pushed ahead vigorously during the summer. The charter of a local dragger for three one-week cruises enabled Mr. W. C. Schroeder to explore the deep water along the edge of the continental shelf between New York and Nova Scotia. This is a region beyond the depth of commercial fishing. In an area on the Nova Scotian slope an abundant catch of red fish was obtained, the report of which has been given freely to commercial fishing interests. It was also found that lobsters are sufficiently numerous beyond the 80-fathom contour to indicate that a profitable fishery might be developed. At slighly greater depths, numbers of large crabs may also be taken. The collections of fish have included several specimens apparently new to science and will add greatly to our knowledge of the distribution of many known species. In particular these catches have shown that several of a northern origin range southward into this region.

Dr. P. F. Scholander and Dr. L. Van Dam have both done distinguished work on the physiology of marine animals. They are studying the physiological mechanism by which fish secrete gas into the swim bladder in order to maintain their buoyancy at depth. By taking advantage of the deep water fishing expeditions of Mr. W. C. Schroeder, they have been able to extend the depth range at which such studies have been made one hundred fold. The result has been to find that the inert gas nitrogen, in addition to oxygen, is apparently secreted into the swim bladder against great pressure. This is a completely novel finding. Studies of the blood chemistry of the deep living fish have not shown any unique property which would explain the phenomenon of gas secretion.

Dr. D. R. Norton, who had previously spent two summers at the Institution on Fellowships, has recently become associated with the U. S. Geological Survey where he is charged with developing work in oceanographic chemistry. He comes to our staff on a part time appointment which will permit him to work at Woods Hole during the summer. This arrangement promises to be of great mutual value to the Institution and to the Survey.

The study of shellfish problems, made under contract with the Commonwealth of Massachusetts, is continuing. The original objective was to find practical methods of clam farming. It has now become apparent that clams cannot be grown profitably on open sand flats because of the depredation of predators. This conclusion is confirmed by simultaneous studies by the Fish and Wildlife Service. While this attempt has been abandoned we have learned much about the biology of the conchs and horseshoe crabs, which are the principal predators. Mr. H. J. Turner and Dr. D. L. Belding for a time investigated the possibility of growing clams in artificial ponds where predation and other conditions can be better controlled, by constructing such a pond in a marsh at Cotuit, but the local problems of control proved extremely difficult. During the latter part of the year attention was turned to an extensive study of the clam flats in Boston Harbor. This is the one great area in Massachusetts where clams are still plentiful. Because of pollution clam digging is carefully controlled by the State and there is an extensive record going back over many years which should enable much to be learned about the effect of digging on the maintenance of the clam crop. At the end of the year this study is continuing.

Our present active interest in estuaries was originally stimulated by the necessity of knowing more about the conditions under which shellfish live. The first estuary studies was Barnstable Harbor, where our shellfish studies started. Dr. J. C. Ayers, during the year, completed a report on the hydrography of this harbor

The study of Great South Bay, and Moriches Bay, Long Island, initiated in 1951 for the towns of Islip and Brookhaven, has now been brought to completion. This investigation has provided a hydrographic description of these coastal bays which are typical of the Atlantic coast, and has included the effects of opening and closing of the inlets which frequently occurs in such situations. These particular bays were of interest because conditions developing over many years had rendered them unfit for the growth of oysters. It has become apparent that these bays are now seriously polluted by the great numbers of duck farms which have been installed along their tributary streams and that this pollution has favored the growth of a peculiar and excessive flora of planktonic algae in the bay water. This situation has provided Dr. F. A. Richards with an unusual opportunity to study the transformations which organic pollutants undergo in natural water bodies.

Dr. J. H. Ryther has also made good use of the situation in the Long Island bays to study the conditions which give rise to the peculiar plankton flora which develops each summer. By comparing the growth of these algae with that of the species more usually found in such bays under controlled conditions of temperature, salinity, nutrient balance, he has found that the phytoplankton which are now found in these bays respond optimally to the conditions now prevalent and thus are able to outgrow the more normal flora. Dr. J. H. Ryther's studies have been supported by a grant from the National Science Foundation.

Oceanographic and geological surveys of the Massachusetts Bay area are continuing under the direction of Mr. D. F. Bumpus and Dr. W. S. Butcher. The field work will be completed by spring and will add much to our knowledge of inshore and estuarine phenomena. Mr. H. Stommel and Mr. H. G. Farmer, Jr., have been writing a major book, "On the Nature of Estuarine Circulation". Their approach is experimental and theoretical, but the two studies complement each other.

The study of estuaries, initiated by the biologists and which appeared to have deflected them in to physical oceanography, has now completed its cycle. Dr. B. H. Ketchum has examined theoretically how to combine the equations for the water exchange in estuaries with the growth and death curves for the floating populations of animals and plants. He has been able to analyze the relative importance of dilution, predation, and natural death on the distribution of coliform bacteria arising from pollution in the Raritan River, and has found that the antibiotic action of sea water is the dominating factor. This work was done under a grant from the U. S. Public Health Service. Mr. John P. Barlow, a visiting investigator in the laboratory, has followed this lead in studying the endemic population of zooplankton in a near-by salt pond. He has shown that the characteristic pond species can maintain themselves only in those parts of the pond where their growth is great enough to over-balance the water movements tending to carry them out to sea. These are brilliant applications of hydrography to biological studies.

As an outgrowth of studies on inshore oceanography such as the Institution has made in the offing of New York, in Raritan Bay and in Great South Bay we are called on increasingly by responsible governmental agencies and civilian organizations for advice on practical aspects of the control of conditions in tidal waters. One of the important areas in this connection is

Delaware Bay where a variety of interests are, at least potentially, in conflict. The bay is the site of a valuable oyster industry. Along the river the community is concerned with the freshness of the water used for industrial purposes and with the problem of waste disposal. Upstream the construction of dams for the diversion of Delaware River water to the water supply of New York City has raised the question of the effects of diversion of the river water on conditions in the lower river and bay. It is clearly important that the hydrography of this area be understood as thoroughly as possible.

During the past year Dr. Ketchum has devoted much time to collecting and analyzing the available data on the region. Mr. A. R. Miller has been "loaned" to Rutgers University and has been engaged in field studies in Delaware Bay being conducted by Dr. H. H. Haskins of that institution. These studies have not been confined to the Bay itself, but have extended offshore where they supplement our knowledge of the general coastal circulation.

Dr. P. D. Trask and Mr. H. C. Stetson have both completed long manuscripts on the sediments of the western Gulf of Mexico. Mr. Stetson's studies of the collections from the eastern Gulf are progressing as rapidly as the analyses of the samples permit.

We are continuing to experience trouble in bridging the gap between the development of new instruments and their use for research purposes. We have three competing designs for deep bathythermographs at present under test. One of them is more than three years old. Mr. Klebba's five-year temperature recorder, although completed more than two years ago, has only recently been set out where useful scientific data can be obtained. His 400-day current meter has yet to be used, although there is some hope that the group at Miami will soon use this excellent instrument. In short, the practical sea-going oceanographer tends to stick to tried and proven methods.

Perhaps worthy of mention is a new camera being built by Mr. L. D. Hoadley for studying sand ripples. This will take 8,000 pictures a few seconds apart so that it should be possible to study the relative importance of long period swell, and bottom currents, in the transport of sand on exposed bottoms. There is hope that this device will be in the water before long. Mr. D. M. Owen has much improved his various cameras and technique during the past year, and an impressive catalog of bottom photographs is now growing.

As a part of the shellfish studies, Mr. Owen has helped Mr. Arthur Posgay in an attempt to determine by photographic means the density of sea scallops on the fishing beds. The object is to gain an estimate of the efficiency of the dredges now in use. The result of one successful cruise has been encouraging, but it is evident from several failures that more intensive effort and close collaboration between photographer and biologist are necessary if results are to be gained from systematic surveys with the camera which justify the cost and effort.

The wave research group at New York University has been considerably strengthened during the past year and we have agreed to supply some of the much needed open ocean wave records so that the wave forecasting procedures can be improved. The greatest need is for a wave recorder that can be used from our PBY plane. Various schemes are under study, but meanwhile Mr. J. R. Bronk has gone ahead with an upside-down echo sounder which gives promise of recording at least moderate seas and swells in a convenient manner from a ship. Several other possible systems for recording the characteristics of waves in deep water are under active study at the close of the year.

In June the National Research Council sponsored a three-day symposium on needs for new and improved oceanographic instruments. Mr. von Arx, Mr. Vine, and Dr. Hersey each presented a paper. Since practically all aspects of the instrumental needs were discussed, the symposium amounted to a short, intensive course in modern oceanography. Mr. Iselin is serving as one of the editors of the resulting publication in which all twelve papers and the significant discussion will appear.

It would require too much space here to summarize our contribution to the success of this symposium or even to list the instruments that are at present being worked on here. There is no lack of ideas for new instruments. The problem is to persuade the designer or builder of the instrument to use it sufficiently so that it becomes part of the research program. Few instruments are fully developed and put into routine use by the original designer. The "debugging" period is usually a very slow process.

A paper has been prepared by Dr. Redfield on the tidal phenomena of the Woods Hole region. Analysis of the tidal records shows that in Vineyard and Nantucket Sounds the tidal ranges, and the times of high water and slack water as they vary from place to place, are to be explained by the mutual interaction of tidal waves which enter the Sounds from their opposite ends. The interference of these waves also explains the diurnal irregularity of the tide at Woods Hole and certain peculiar features of the Woods Hole tide record and of the flow through Woods Hole Passage.

Forty-three scientific papers have been prepared for publication during 1952. These include two major papers for *Papers in Physical Oceanography and Meteorology*. The monograph "Marine Fouling and Its Prevention", prepared at the conclusion of the War, was published in September by the U. S. Naval Institute. The following publications of the Institution during the past year are listed by contribution number, author, and title:

	Contr. No.
Bigelow, H. B., and W. C. Schroeder. A new species of the cyclostome Genus Paramyxine from the Gulf of Mexico. *Breviora*, No. 8: 10 pp., 6 text figs.	610
Bunker, A. F. Measurements of the vertical water vapor transport and distribution within unstable atmospheric ground layers and the turbulent mass exchange coefficient. *Pap. Phys. Ocean. Meteorol.*, 12 (3): 42 pp., 27 text figs.	618
Bunker, A. F. 3.13. Recognition of the presence of convective currents within a non-saturated turbulent layer of the atmosphere. In: International Symposium on Atmospheric Turbulence in the Boundary Layer, Massachusetts Institute of Technology, 4–8 June 1951. *Geophys. Res. Pap. Air Force Cambridge Research Center*, No. 19: 309–322	572
Collins, G. B. Factors influencing the orientation of migrating anadromous fishes. *Fish. Bull.* 73, *Fish. Bull., Fish and Wildlife Service*, 52: 375–396, 7 text figs.	585
Ericson, D. B., M. Ewing, and B. C. Heezen. Turbidity currents and sediments in the North Atlantic. *Bull. Amer. Assoc. Petr. Geol.*, 36 (3): 489–511, 4 text figs.	604
Ford, W. L., and A. R. Miller. The surface layer of the Gulf Stream and adjacent waters. *J. Mar. Res.*, 11 (3): 267–280, 7 text figs.	619
Hersey, J. B., H. R. Johnson, and L. C. Davis. Recent findings about the deep scattering layer. *J. Mar. Res.*, 11 (1): 1–10, 3 text figs.	562
Hersey, J. B., C. B. Officer, H. R. Johnson, and S. Bergstrom. Seismic refraction observations north of the Brownson Deep. *Bull. Seismol. Soc., Amer.*, 42 (4): 291–306, 14 text figs.	583
Iselin, C. O'D. The Gulf Stream system. *Proc. Amer. Phil. Soc.*, 96 (6): 660–662	612
Ketchum, B. H., J. C. Ayers, and R. F. Vaccaro. Processes contributing to the decrease of coliform bacteria in a tidal estuary. *Ecology*, 33 (2): 247–258, 4 text figs.	561
Ketchum, B. H., and W. L. Ford. Rate of dispersion in the wake of a barge at sea. *Trans. Amer. Geophys. Union*, 33 (5): 680–684, 3 text figs.	567
Kierstead, H. A. Bottom pressure fluctuations due to standing waves in a deep, two-layer ocean. *Trans. Amer. Geophys. Union*, 33 (3): 390–396, 1 text fig.	582
Laidlaw, F. B. The history of the prevention of fouling. *Proc. U. S. Naval Inst.*, 78 (7): 769–779	613
Machlup, S. Theoretical model for sound scattering by marine crustaceans. *J. Acoust. Soc., Amer.*, 24 (3): 290–293	569
Malkus, J. S. Recent advances in the study of convective clouds and their interaction with the environment. *Tellus*, 4 (2): 71–87	595
Malkus, J. S. The slopes of cumulus clouds in relation to external wind shear. *Quart. J. Roy. Meteorol. Soc.*, London, 78 (338): 530–542, 9 text figs., Pls. 3–4	609
Malkus, J. S., and A. F. Bunker. Observational studies of the air flow over Nantucket Island during the summer of 1950. *Pap. Phys. Ocean. Meteorol.*, 12 (2): 50 pp., 47 text figs.	617
Malkus, W. V. R., and M. E. Stern. Determination of ocean transports and velocities by electromagnetic effects. *J. Mar. Res.*, 11 (2): 97–105, 2 text figs.	608
Mather, F. J., III. Three species of fishes, Genus Seriola, in the waters of Cape Cod and vicinity. *Copeia*, 1952 (3): 209–210	599

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Mather, F. J., III. Sport fishes of the vicinity of the Gulf of Honduras, certain Caribbean islands and Carmen, Mexico. *Proc. Gulf and Caribbean Fish. Inst.*, 4th Ann. Session: 118–129	611
Mather, F. J., III, and H. A. Schuck. Additional notes on the distribution of the blackfin tuna (*Parathunnus atlanticus*). *Copeia*, 1952 (4): 267	606
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Moore, H. B. Physical factors affecting the distribution of Euphausids in the North Atlantic. *Bull. Mar. Sci., Gulf and Caribbean*, 1 (4): 278–305, 24 text figs.	581
Parker, F. L. Foraminifera species off Portsmouth, New Hampshire. *Bull. Mus. Comp. Zool.*, 106 (9): 391–423, 6 pls.	589
Parker, F. L. Foraminifera distribution in the Long Island Sound-Buzzards Bay area. *Bull. Mus. Comp. Zool.*, 106 (10): 427–473, 5 pls., 6 tables, 2 text figs.	590
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Phleger, F. B. Foraminifera ecology off Portsmouth, New Hampshire. *Bull. Mus. Comp. Zool.*, 106 (8): 315–390, 25 text figs., tables	591
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Riley, G. A. Hydrography of the Long Island and Block Island Sounds. *Bull. Bingham Ocean. Coll.*, 13 (3): 5–39, 11 text figs.	578
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Schell, I. I. On the role of ice off Iceland in the decadal air temperatures of Iceland and other areas. *J. du Cons.*, 18: 11–36, 1 text fig.	603
Schevill, W. E. On the nomenclature of the Pacific gray whale. *Breviora*, No. 7: 3 pp.	626
Sears, M. Notes on siphonophores. 3. *Nectopyramis spinosa*, n. sp. *Breviora*, No. 3: 4 pp., 1 text fig.	607
Stommel, Henry. 2.4. Streaks of natural water surfaces. In: Symposium on Atmospheric Turbulence in the Boundary Layer, Massachusetts Institute of Technology, 4–8 June 1951. *Geophys. Res. Pap., Air Force Cambridge Research Center*, No. 19: 145–154	537
Stommel, H., and H. G. Farmer. Abrupt change in width in two-layer open channel flow. *J. Mar. Res.* 11 (2): 205–214, 3 text figs.	616

	Contr. No.
Turner, H. J., Jr. Fourth report on investigations of the shellfisheries of Massachusetts. Comm. Mass., Dept. Conserv., Div. Mar. Fish., 21 pp., 2 text figs.	615
von Arx, W. S. Notes on the surface velocity profile and horizontal shear across the width of the Gulf Stream. *Tellus*, 4 (3): 211–214, 3 text figs.	621
von Arx, W. S. A laboratory study of the wind-driven ocean circulation. *Tellus*, 4 (4): 311–318, 4 text figs.	622
Woodcock, A. H. Atmospheric salt particles and raindrops. *J. Meteorol.* 9 (3): 200–212, 16 text figs.	563
Woods Hole Oceanographic Institution. Marine fouling and its prevention. U. S. Naval Inst., Annapolis: 388 pp.	580
Wyman, J., Jr., P. F. Scholander, G. A Edwards and L. Irving. On the stability of gas bubbles in sea water. *J Mar. Res.*, 11 (1): 47–62, 5 text figs.	600

Vessels

Shortly after New Year's Day, Atlantis and Albatross III (a U. S. Fish and Wildlife Service craft) departed from Woods Hole on a cruise to the lower latitudes of the North Atlantic from which they did not return until late May. During the voyage the Atlantis suffered two serious accidents, one the loss of the mizzen mast and sail off the mouth of the Amazon, and then a few weeks later, the breaking of the propeller shaft. The second accident fortunately occurred not far at sea from the Guantanamo Naval Base where repairs were promptly effected.

After a six-weeks' overhaul and the fitting of a new spar, the Atlantis sailed again the middle of July on another long sea voyage, this one as far south as Rio de Janeiro. She returned from this cruise (No. 180) shortly before the end of the year.

Caryn, except for one voyage to Bermuda in May, sailed on short cruises out of Woods Hole throughout the year.

Bear, a 100-foot diesel craft, which was chartered for the summer, operated also from the home port, often in company with Caryn. In September they carried out a joint hydrographic reconnaissance of the waters southeast of New England, the offshore stations being located in the northern edge of the Gulf Stream. In November the Bear was purchased by the Institution under arrangements with the Navy to underwrite the costs over a period of two years.

Albatross III, a diesel trawler, which it will be recalled, was turned over to the Institution's operation by the Fish and Wildlife Service in 1951, was taken back by that Service in June.

Added to our fleet in April was a Navy PBY6A airplane, loaned to the Institution to carry out certain scientific operations at sea. This marks what is believed the first long period assignment of an aircraft to make oceanographic observations. Its first trip was to Puerto Rico where it carried out observations in Trade Winds belt. In November, and again in December, meteorological flights to Bermuda were made.

No changes took place in the smaller boats of the Institution, — Asterias, Mytilus, and Claire. Mytilus, which has had its engine removed, remained throughout the year in wet storage.

An addition to the small-craft pool occurred in October when Mr. Samuel A. Peck, a member of the Woods Hole Oceanographic Associates, presented the Institution with a 45-foot twin, gas screw sport-fishing cruiser called Allure. The gift was accepted with the understanding that if the boat did not prove to be practicable for the Institution to operate, then it would be disposed of as deemed to the best interests of the Institution.

In an effort to relieve the need for additional research vessels for summer work, and to further increase the operational efficiency of the fleet an inspection was made of the motor ship Hampton Roads at Norfolk, Virginia, in the Spring of 1952. It was found, however, that after hauling out on the marine railway, the condition of the under parts of the hull did not warrant the expense of repair, and therefore this acquisition was reluctantly abandoned.

Some hopes of new oceanographic construction, nevertheless, were provided by the Geophysics and Geography Committee of the Research and Development Board which met at Woods Hole in June and passed a resolution calling attention to the need for modern designed vessels for oceanography. They requested that a study be made of the problem, and recommendations submitted, which might lead to the desired construction. Later in the year the Institution accepted a contract with the Office of Naval Research to make a report on pre-design studies of superior oceanographic ships for oceanographic research. This engineering study which was sub-contracted to the Marine and Fisheries Engineering and Research Institute Inc., continued at the year's end.

Plant

The largest expenditure of funds for plant improvement during the year pertained to the renovation of the barn on the former Fay property at Woods Hole, whereby this building was converted to a summer-time dormitory. The ground floor contains three apartments, and the second floor eight large rooms for bachelor quarters. Included in the improvements are a basement and attic storage space, and the hard surfacing of the roads leading to the property. We have now provided for living accommodations for students and others who work at the Institution during the summer, and who have limited financial means to pay higher rentals.

Challenger House, which provides rooms the year round for women working at the Institution, served cafeteria style meals to Institution personnel. Due to the small number of persons patronizing the cafeteria during the winter, however, this service was suspended.

Previous record has been made in last year's annual report of the Navy's desire to erect a new laboratory building on a proposed site adjacent to our main building at the waterfront, Woods Hole. Negotiations between the Navy and the Marine Biological Laboratory (the owner of the site) proceeded slowly during the year. The Navy announced in November, however, that it was taking the land for the site of the new laboratory which the Institution will be asked to operate. In the meantime space continues to be extremely crowded in our buildings and on the restricted water front property, all of which handicaps the efficient performance of work, and also adds materially to the danger of fire.

Personnel

The Research Staff, the heart of the Institution, and responsible for the volume and quality of the productive research, numbered 189. A roster of all the Institution personnel as of July 1, 1952, is shown below. The list for 1951 is included for comparison.

	1951	*1952*
RESEARCH STAFF *		
Full time:		
At Woods Hole	70	96
Off campus	12	6
Part time:		
At Woods Hole	40	45
Off campus	16	21
Fellowship holders	14	14
Visiting investigators	9	7
ADMINISTRATIVE STAFF		
Department Heads and Assistants	11	11
Secretaries and Clerks	24	22
General Maintenance and Service	51	55
Crews of Vessels	61	41
TOTAL	308	318

* Includes 59 Staff Appointees and 130 others

The part time members of the research staff, listed above, refer mostly to those who are affiliated with universities and who spend their summers at Woods Hole, often bringing graduate students to work at the Institution.

It is with pleasure that we record the appointment to the research staff of the following:

Richard H. Backus	Research Associate in Marine Biology
Robert H. Brockhurst	Research Associate in Mathematics
Elizabeth T. Bunce	Research Associate in Physics
Joseph Chase	Research Associate in Physical Oceanography
Frank T. Dietz	Research Associate in Underwater Acoustics
Willard Dow	Electronic Engineer
David H. Frantz, Jr.	Research Associate in Engineering
John F. Holmes	Research Associate in Engineering
Sydney T. Knott, Jr.	Research Associate in Underwater Acoustics
Donald P. Martineau	Research Associate in Physical Oceanography
Kenneth G. McCasland	Research Associate in Meteorology
Arthur R. Miller	Research Associate in Physical Oceanography
Daniel R. Norton	Associate in Chemical Oceanography
D. Jane Roberg	Research Associate in Physics
Helen M. Roberts	Associate in Mathematics
Karl E. Schleicher	Research Associate in Engineering
Per F. Scholander	Physiologist
Paul F. Smith	Associate in Oceanography
Levie Van Dam	Research Associate in Physiology
Arthur D. Voorhis	Research Associate in Underwater Acoustics

Mr. Robert C. Moses, Engineer, it is regretted, resigned from the staff during the year.

Dr. Mary Sears of our staff visited Europe during the Fall and represented the Institution at the 50th Anniversary Meeting of the International Council for the Exploration of the Sea at Copenhagen, and also she attended a meeting of the International Joint Commission of Oceanography at Monaco.

Record is made in this section of the action of the Members of the Corporation, at their annual meeting in August, of the establishment of a class of Honorary Trustees. Two members of the Board (Dr. Henry B. Bigelow and Dr. E. G. Conklin) at their own request, were transferred to honorary trustee status. Also should be noted the election of four new members to the Corporation, viz., Dr. J. S. Coles, Mr. Gerard Swope, Jr., Mr. Francis C. Ryder and Dr. E. B. Wilson, Jr.; the first two also being elected to the Board of Trustees.

It is with deep regret that the death in November of Dr. E. G. Conklin, Professor Emeritus of Princeton University, and an Honorary Trustee of the Institution, is recorded. The facts that he was a Trustee of the Institution since its founding, and has given devoted service to the Institution, marks his passing as a distinct loss.

Dr. Athelstan F. Spilhaus, Chairman of the Scientific Advisory Committee visited the Institution March 14–17, and submitted a report of his committee for subsequent action to the Executive Committee.

Captain Adrian K. Lane, who had been Master of Atlantis for more than six years, came ashore on July 8th and became Port Captain of our fleet.

The following persons were awarded honoraria, grants or fellowships, during the year:

Arrhenius, Gustaf
Ayers, John C.
Barlow, John P.
Bursa, Adam
Butler, Patrick
Creitz, Grace I.
Ewing, W. Maurice
Fofonoff, Nick
Francis, J. R. D.
Frodyma, Michael M.
Holmes, Robert W.
Huntsman, A. G.
Leavitt, Benjamin B.
Livesay, Ann
Miller, Arthur R.
Montgomery, Raymond B.
Neumann, Paul G.
Norton, Daniel R.
Plunkett, Mary A.
Postma, Hendrik
Riley, Gordon A.
Rossby, Carl-G.
Said, Rushdi
Van Dam, Levie
Watson, Stanley W.

It is desired to acknowledge under this section a grant from the Rockefeller Foundation to be used during a period of three years to support two major appointments in the field of marine biology. This has permitted the appointment of Dr. Per F. Scholander, an experienced and able physiologist. The other appointment is pending the selection of a qualified candidate.

The Institution also received a grant from the National Science Foundation for Research Training in Oceanography. This enabled us to award fellowships to eight investigators. Under this arrangement Mr. Patrick Butler of Harvard University, Miss Grace I. Creitz of Moravian College for Women, Dr. Michael M. Frodyma of George Washington University, Dr. Benjamin B. Leavitt of the University of Florida, Miss Ann Livesay of the University of Kentucky, and Dr. Mary A. Plunkett of Vassar College worked for the summer at Woods Hole, while Dr. John P. Barlow was enabled to visit the Oceanographic Laboratory of the University of Washington at Friday Harbor.

The grant from the National Science Foundation relieved the Institution of the expense of its program of summer fellowships for graduate students and junior instructors from the universities and colleges. This program has been one of the most successful means of recruiting oceanographers and disseminating interest in the science.

During the year opportunity has been taken to bring the Institution and its objectives closer into the minds of the community by inviting groups of local people from time to time to inspect the laboratory and visit the research ships berthed at the water front.

Out of this activity and interest has developed a desire on the part of some of these persons who have a sustaining interest in the sea, to seek a closer and continuing association with the scientific work of the Institution. This development (earlier approved by the Board of Trustees) has led to the establishment of a non-profit organization patterned after the laws of Massachusetts called the WOODS HOLE OCEANOGRAPHIC ASSOCIATES. Mr. Gerard Swope, Jr. was elected president of the Associates at a meeting held in New York, April 24, 1952, and the first annual meeting was held August 16, 1952. At the close of the year a body consisting of an Executive Committee and a membership of some forty odd had become established. Provision has been made in the by-laws for corporate and institutional membership should such an expansion appear indicated at a later date.

The following visitors were among those who spent a day to a few weeks at the Institution at one time or another during the year:

PROF. JOHAN T. RUUD, University of Oslo, Norway
DR. A. W. H. NEEDLER, Fisheries Research Board of Canada, St. Andrews, N. B.
DR. D. CARROLL, London University, England
DR. A. GRZYWIENSKI, Hydrologisches Inst., Austria
COMMANDANT JACQUES-YVES COUSTEAU, French Navy
DR. PIERRE DANEL, Neyrpic Laboratories, Grenoble, France
PROF. RAMON IRIBARREN-CAVANILLES, Madrid, Spain
DR. YVES LEGRANDE, Museum National d'Histoire Naturelle, Paris, France
DR. GUSTAF ARRHENIUS, Kagghamra, Sweden
DR. FRITZ GASSMAN, Zurich, Switzerland
DR. HENDRIK POSTMA, Zoologisch Station, Den Helder, Holland
PROF. M. FLORKIN, Univ. Liege, Belgium
DR. A. B. JOLY, Univ. St. Paulo, Brazil
PROF. S. P. DONTAS, Greek Hydrobiological Inst., Athens, Greece
DR. G. E. R. DEACON, National Institute of Oceanography, England
MR. JOHN FRANCIS, Imperial College, London University
Mr. M. S. LONGUET-HIGGINS, Trinity College, Cambridge Univ., England
DR. ERIK M. POULSEN, I. C. N. A. F., Denmark
DR. W. R. MARTIN, Fisheries Research Board of Canada, St. Andrews, N. B.
MR. IAN S. R. MUNRO, C. S. I. R. O., Cronulla, Australia
DR. ELIO BORGHESE, Univ. Pavia, Italy
DR. A. CRAYA, Grenoble, France

The persons whose names are listed below were members of the Institution (additional to those otherwise listed) for a period of six months or more during the calendar year 1952.

RESEARCH ASSISTANTS, ENGINEERS AND TECHNICIANS

Athearn, William D.
Barbour, L. Hilliard
Bergstrom, Stanley W.
Bernache, Barbara A.
Black, William A.
Bonini, William E.
Brainerd, Suzanne
Cain, Henry A.
Cangiamila, Angelo
Corwin, Nathaniel
Davis, Lee
Day, C. Godfrey
Duys, Gerrit, Jr.
Edwards, Melville E.
Foster, Donald B.
Gessner, Robert E.
Hammond, Willis T.
Hayes, Carlyle R.
Hempstead, Mabel S.
Hoadley, Lloyd D.
Hodgson, Sloat F.
Holland, Lawrence R.
Iselin, Columbus O'D, Jr.
Keen, D. Jean
Kemp, James M.
Lufburrow, Robert A.
McLeod, Jean
Owen, David M.
Palmer, Horace S.
Parson, Donald, Jr.
Pasley, Gale G., Jr.
Pingree, Frederick deW.
Poole, Stanley E.
Posgay, Julius A.
Purinton, Charles S.
Rose, John C.
Shelnut, Eva M.
Shultz, William S.
Stern, Melvin E.
Stilwell, Jean
Vaccaro, Ralph F.
Volkmann, Gordon H.
Wagner, Lansing P.
Williams, Nancy H.
Witzell, Warren E.

JUNIOR TECHNICIANS AND LABORATORY ASSISTANTS

Anderson, Nellie E.
Ash, Adelma S.
Atwood, Barbara
Bowman, Phyllis R.
Bergstrom, Eileen S.
Brown, Joan A.
Cobb, Mary A.
Davis, Priscilla A.
English, Jean
Gallagher, Gloria
Glaeser, Florence E.
Holmes, Doris M.
Lake, Gracie T.
Northrup, Barbara M.
Perry, Barbara L.
Posgay, Marjorie F.
Scharff, Margaret
Schroeder, Elizabeth H.
Spooner, Joanne C.
Tollios, Evangeline P.

ADMINISTRATIVE AND SECRETARIAL

Backus, Jeanne M.
Behrens, Henry G.
Broadbent, Madeline P.
Bryant, Edwin T.
Conlan, Marcus J.
Crocker, Marion W.
Dingwell, Eva Z.
Donald, Mary
Douthart, Dorothy E.
Ferris, Alice H.
Griffin, T. S. Perry
Hatzikon, Kaleroy L.
Mellor, Florence K.
Ortolani, Mary
Ostiguy, Betty P.
Parker, Evelyn M.
Sandblom, John D.
Schnabel, Dorothy L.
Wilson, Esther N.
Young, Anita M.

TECHNICAL SERVICES

Allen, John L.
Archibald, Roy C.
Bailey, Frank A.
Bennett, Paul E.
Blake, Forrest W.
Bodman, Ralph H.
Bowman, Warren O.
Carter, Alwyn L.
Chute, Edward H.
Condon, J. William
Dimmock, Richard H.
Dingwell, Paul E.
Eldridge, Stanley N.
Fisher, Stanley O.
Gallagher, William F.
Gaskell, Fred
Gifford, James E.
Grant, Carleton
Hodgkins, Harry L.
Howland, Myron P., Jr.
Knott, William D.
Lane, Marian O'D.
Morrison, Kenneth
Nelson, Dona E.
Rennie, Thomas D.
Ronne, F. Claude
Spencer, Allard T.
Spooner, Charles E.
Stimpson, John W.
Thayer, Lawrence A.
Vail, Phyllis F.
Walden, Robert G.
Weeks, Robert G.
Whitney, G. G., Jr.
Wing, Carleton R.

MAINTENANCE AND HOUSING

Backus, Harold
Christian, John A.
Cross, Donald E.
Handy, Harry H.
Howes, Elijah S.
Polley, Robert E.
Salthouse, James
Soderland, Ida S.
Solberg, Otto
Sparks, Elizabeth C.
Stansfield, Richard
Turner, Catherine
Wilde, Phillips B.
Wing, Nathaniel R.
Woodward, Fred C. Jr.

OFFICERS AND CREW MEMBERS OF VESSELS, BOATS, AND AIRCRAFT

Atwood, Charles F.
Backus, Cyril
Bailey, James S.
Barstow, Elmer M.
Bosworth, Russell E.
Bradley, John III
Buck, Leo M.
Cabral, John V.
Cavanaugh, James J.
Clarkin, James J.
Colburn, Arthur D., Jr.
Collins, John S.
Conley, William J.
Cook, Hans
Ellis, Kenneth B.
Fay, Donald H.
Frenyea, E. Gerald
Gingrass, Norman
Hempstead, Robert L.
Karlson, Arvid
Kiernan, Clayton F.
L'Heureux, Raymond E.
Lambert, Joseph L.
Lyon, Thomas
Macauley, Franklin A.
Mackey, Malcolm R.
Mannix, Paul B.
Mysona, Eugene J.
Ortiz, Clemente
Pearson, Rowland
Pierce, Samuel F.
Pike, John F.
Poole, Mathew A.
Roderick, Milton
Rose, Lawrence
Ross, Harold W.
Seibert, Harry H.
Shields, William J.
Speight, Carl W.
Waters, Francis V.

April 8, 1953

V. TREASURER'S REPORT

The accounts for the year 1952 have been audited by Messrs. Seamans, Stetson & Tuttle, Certified Public Accountants of Boston.

Endowment Fund Assets and Endowment Fund

The Endowment Fund cash plus the quoted market value of the investments in bonds and stocks at December 31, 1952 totaled $3,600,990.90, an increase of $235,262.96 over the December 31, 1951 total. Of the total amount, $1,291.90 was in cash, $1,202,228 in bonds, a decrease of $14,024.47 over the book value, and $2,397,471 in stocks, an increase of $971,387.90 over the book value.

During the year bonds costing $381,168.81 were sold or redeemed for $382,297.26 which, after adding applicable amortization of bond premiums in the amount of $594.98, resulted in a realized gain of $1,723.43. Stocks and rights with book or assigned values of $164,356.06 were sold for $253,005.30, resulting in a net gain of $88,649.24. The total net gain from all sales or exchanges amounted to $90,372.67, thus bringing the accumulated net realized gain to the Endowment Fund to $224,207.51.

During the year, from the proceeds of the above sales and cash $507,679.61 was invested in bonds and $128,240.58 in stocks, leaving $1,291.90 uninvested at the year-end.

Plant Assets and Plant Funds

Plant Assets increased $100,998.32 during the year. The increase resulted from the following additions to Plant: Laboratory Equipment, $29,407.49; Library Books, $1,200.00; improvements to the Homestead property $23,940.83, and Boats $46,450. The increase in Boats arose from the gift of the motor-boat "Allure", valued at $47,000, less the book value of $550 of a small boat sold.

Current Assets and Current Liabilities

Accounts and Notes Payable, plus Unexpended Grants, exceeded Cash and Receivables by $17,199.86, against a similar figure for last year of $45,447.17, an improvement of $28,247.31. The Notes Payable were reduced $20,000 during the year.

The item "Prepaid Expenses" amounting to $12,473.79, consists of prepaid insurance premiums and discounted interest on Notes Payable.

Deferred Boat Costs increased from $70,528.69 at the end of 1951 to $89,107.07 at the end of 1952. The benefit of these expenses extends over several years, and each year a proportionate part is added to Boat Costs.

During the year $30,974.92 was thus charged to Current Boat Costs, and $14,553.30 was added to Deferred Boat Costs, for improvements to the "ATLANTIS" and "CARYN". In addition, $35,000 was added to Deferred Boat Costs for the purchase of the motor vessel "BEAR".

Included in Deferred Expenses is an item "Maintenance of Homestead, $536.49". This is the unamortized portion of the cost of repairs and improvements at Challenger Hall, and will be charged to Expense in 1953.

The Account Payable "BEAR" amounting to $33,000 represents the balance due on the purchase price of the "BEAR" at December 31, 1952, payable in three equal monthly payments.

The Surplus account increased from $71,190.34 to $104,636.47. This increase, of $33,446.13, is shown in detail on the Balance Sheet.

The Housing and Mess were operated at losses of $5,845.21 and $3,001.32 respectively, which losses were included in overhead costs. The Hall property produced a net income of $1,048.49. The three comparable figures for the previous year were: Housing, loss of $4,067.63; Mess, loss of $2,975.60; and Hall property, net income of $2,072.26.

The total income of the Institution from investments after deducting amortization of bond premiums, amounts to $153,685.24, compared to $157,333.69 for the previous year. Other income, including grants and fees, brought our total Institution income to $205,213.08. Institution charges against income, including our share of cooperative projects, totaled $203,812.72, resulting in an excess of Income carried to Surplus of $1,400.36.

The Institution does contract work for various governmental agencies on a cost reimbursement basis, and during 1952 received a fee for work under these contracts amounting to $49,845.21, which amount is included in the Institution income.

In the Income and Expense statement the item "Cooperative Projects, $3,755.97" represents the expenditures by the Institution on Cooperative Projects, amounting to $48,820.49, less the total of grants and contributions, amounting to $45,064.52 received from the following: U. S. Public Service; Commonwealth of Massachusetts; Rockefeller Foundation; National Science Foundation, and E. I. duPont de Nemours & Co. Included in the above is Grants and Fellowships made by the Institution from the National Science Foundation grant of $5,453.70.

The return on the investments held at the year-end was at the rate of 4.26% on the market value, 5.8% on the book value, and 6.36% on the original book value of the Endowment.

The Balance Sheets and Statement of Income and Expenses are appended.

EDWIN D. BROOKS, JR., *Treasurer*

BALANCE SHEET

As of December 31, 1952

ENDOWMENT FUND ASSETS

Bonds (Less Reserve for Amortization of Bond Premiums $1,962.79)		$1,216,252.47	
Quoted Market Value	$1,202,228.00		
Stocks		1,426,083.10	$2,642,335.57
Quoted Market Value	2,397,471.00		
	$3,599,699.00		
Cash			1,291.90
			$2,643,627.47

Note: Bonds having a book value of $399,829.05 are specifically allocated as collateral on the Institution's indebtedness to The New England Trust Company.

PLANT ASSETS

Laboratory Plant:			
Land		$27,072.32	
Buildings		336,564.86	
Laboratory Equipment		80,149.12	
Library		23,200.00	$466,986.30
Ketch "Atlantis":			
Construction	$218,674.47		
Equipment	41,462.50	$260,136.97	
Ketch "Caryn"		98,275.43	
Motor Boat "Allure"		47,000.00	
Small Boats and Equipment		10,028.85	415,441.25
Hall Property			26,500.00
Homestead			134,552.41
			$1,043,479.96

BALANCE SHEET

As of December 31, 1952

ENDOWMENT FUNDS

ENDOWMENT FUND — GENERAL	$2,000,000.00	
ENDOWMENT FUND — FOR UPKEEP OF PLANT	419,419.96	$2,419,419.96
Add accumulated net gain on securities called or sold		224,207.51
		$2,643,627.47

PLANT FUNDS

PLANT FUND — GENERAL			$687,328.79
PLANT FUND RESERVE — TRANSFERRED IN PRIOR YEARS FROM CURRENT SURPLUS		$302,152.85	
Add appropriation from Current Funds:			
Laboratory Equipment	$29,407.49		
Improvements to Homestead	23,940.83		
Library — Book Purchases	1,200.00	54,548.32	
		$356,701.17	
Deduct Book Value of Boat Sold		550.00	356,151.17
			$1,043,479.96

BALANCE SHEET

As of December 31, 1952

(Concluded)

CURRENT ASSETS

Cash:			
Main Account		$116,677.35	
Operating Accounts		48,415.72	
Office and Boat Funds		2,028.92	$167,121.99
Accounts — Receivable:			
Governmental Agencies:			
Invoiced		$ 37,525.36	
Not Invoiced, Materials and Services	$145,764.05		
Not Invoiced, Use of Boats	23,888.97	169,653.02	
		$207,178.38	
Co-operating Institutions		8,797.46	
Other Accounts Receivable		36,623.73	252,599.57
Supplies and Work-in-Progress			32,718.98
Prepaid Expenses			12,473.79
Deferred Expenses:			
Boat Expenses		$ 54,107.07	
Motor Vessel "Bear"		35,000.00	
Maintenance of Homestead		536.49	89,643.56
			$554,557.89

BALANCE SHEET

As of December 31, 1952

(Concluded)

CURRENT LIABILITIES

Accounts — Payable:				
Sundry Creditors			$16,179.05	
Withheld from Employees for Taxes, Insurance, etc.			11,563.96	
Sundry Accrued Expenses			12,719.44	$40,462.45
Account — Payable "Bear"				33,000.00
Notes — Payable (Secured by Bonds Having a Book Value of $399,829.05)				340,000.00
Unexpended Grants				23,458.97
Reserve for Equipment Purchases				13,000.00
Surplus:				
Periodic Replacement Fund:				
Balance, December 31, 1951		$143,022.82		
Appropriation, 1952		4,000.00	$18,322.82	
General:				
Balance, December 31, 1951		$56,867.52		
Add:				
Excess of Income — Exhibit B	$1,400.36			
Gifts	1,025.19			
Depreciation Charged to Overhead Expense	20,315.31			
Adjustments for Prior Periods	6,705.27	29,446.13	86,313.65	
Total Surplus, December 31, 1952				104,636.47
				$554,557.89

INCOME AND EXPENSE STATEMENT

Year Ended December 31, 1952

INCOME:			
Investments:			
Interest	$ 35,608.58		
Dividends	118,720.25	$154,328.83	
Less Amortization of Bond Premiums		643.59	$153,685.24
Fees on Government Contracts			49,845.21
Hall Property (Net Operating Income)			1,048.49
Sundry			634.14
			$ 68,948.68
EXPENSES:			
Operating		$ 86,996.02	
Institution Projects		34,347.73	
Co-operative Projects		3,755.97	
Operation of Vessels		1,741.63	
Interest Paid		9,423.05	136,264.40
			$205,213.08
PAYMENT FOR PLANT ITEMS FROM CURRENT FUNDS:			
Laboratory Equipment		$29,407.49	
Alterations at Homestead (New Dormitory)		16,956.46	
Equipment at Homestead (Challenger Hall and Dormitory)		6,984.37	
Library Books		1,200.00	
		$54,548.32	
Reserved for Equipment Purchases		13,000.00	67,548.32
Excess of Income to Surplus — Exhibit A			$1,400.36

APPENDIX

ATLANTIS

Cruise No.	Departure and Return	Days Duration	Ports of Call	Scientist-in-Charge
178	15 January		Woods Hole to Bermuda	Ketchum
	19 January	5	Arrived Bermuda	
	22 January		Bermuda to	
	9 February	18	Las Palmas	
	11 February		Las Palmas to	
	21 February	10	Dakar	
	26 February		Dakar to	
	11 March	13	Recife	
	17 March		Recife to	
	12 April	26	Port of Spain	Fuglister
179	17 April		Port of Spain	
	26 April	9	to Guantanamo	
	10 May		Guantanamo to	
	28 May	18	Woods Hole	
180	19 July		Woods Hole to Ponta	Heezen
	4 August	14	Delgada, Azores	
	7 August		Ponta Delgada	
	25 August	18	to Dakar	
	28 August		Dakar to	
	17 September	20	Recife	
	20 September		Recife to Rio de	
	4 October	14	Janeiro	
	14 October		Rio de Janeiro	Fuglister
	27 October	13	to Recife	
	30 October		Recife to Port	
	22 November	23	of Spain	
	26 November		Port of Spain to	
	7 December	12	St. Georges	
	10 December		Bermuda to	
	14 December	4	Woods Hole	

CARYN

Cruise No.	Departure and Return	Days Duration	Ports of Call	Scientist-in-Charge
	January	Short Cruises		Hersey & Vine
	February	Short Cruises		Hersey & Vine
C-29	29 March		Woods Hole to Bermuda	Vine
	5 April	8	Arrived Bermuda	
	24 April	20	Arrived Woods Hole	
C-30	28 April		Woods Hole to Boston	Bumpus
	20 May	23	Boston to Woods Hole	
C-31	22 May	3	Short Cruise	Hersey
C-32	18 June	3	Short Cruise	Officer
C-33	26 June	1	Short Cruise	Dietz
C-34	30 June	4	Short Cruise	Hersey
C-35A	8 July	1	Short Cruise	Hersey
C-35B	9 July	1	Short Cruise	Hersey
C-36	14 July	4	Short Cruise	Hersey
C-37	20 July	7	Short Cruise	Watson
C-38	31 July		Hudson Canyon	Leavitt
	12 August	13	Return to Woods Hole	
C-39	August			
C-55	December		Short Cruises	

ALBATROSS III

Cruise No.	Departure and Return	Days Duration	Ports of Call	Scientist-in-Charge
A-42	24 January		Woods Hole to	Richards
	28 January	4	Bermuda	
	30 January		Bermuda to	
	21 February	22	Dakar, Africa	
	26 February		Dakar to Recife,	
	11 March	14	Brazil	
	18 March		Recife, Brazil to	
	11 April	24	Port of Spain, Tr.	
A-43	17 April		Port of Spain to	Heezen
	23 April	7	Guantanamo Bay	
	7 May		Guantanamo Bay to	
	27 May	20	Woods Hole	
A-44	18 June		Short trips	Hersey
	24 June	Left for Bayonne, New Jersey and returned to Custody of U. S. Fish and Wildlife Service		

BEAR

July thru December — Short trips to Sea. Scientist-in-Charge — Hersey

PBY — NO. 46683

PBY — Arrived 19 April 1952. Local flights April and May

Cruise No.	Departure and Return	Days Duration	Ports of Call	Scientist-in-Charge
P-2	18 June	19	New Bedford to Miami Miami to San Juan, Puerto Rico Puerto Rico to St. Croix and St. Thomas to Ramey A. F. B., P. R. to Roosevelt Roads to Jacksonville, Florida	Bunker
	7 July		to New Bedford	
	August		Local Flights	
P-4	2 September	1	New Bedford — Cashes Ledge , Maine and return	von Arx
P-6	28 October	3	Otis A. F. B.— Elizabeth City, North Carolina	Frantz
	30 October		Return to New Bedford	
P-9	5 November	4	New Bedford to Kindley A. F. B.	Bunker
	8 November		Bermuda, return to New Bedford	
P-12	24 November	2	New Bedford to Elizabeth City, N. C.	von Arx
	25 November		Return	
P-21	17 December	4	New Bedford — Kindley A. F. B., Bermuda	
	20 December		Return	

CAP'N BILL II

Cruise No.	Departure and Return	Days Duration	Locality	Scientist-in-Charge
1	20 June 27	7	Atlantic Slope, Hudson Canyon to Veatch Canyon	Schroeder
2	10 July 17	7	Atlantic Slope, Veatch Canyon to Lydonia Canyon	Schroeder
3	23 July 30	8	Atlantic Slope, Lydonia Canyon to offing of LaHave Bank	Schroeder

List of Contributions

LIST OF CONTRIBUTIONS

FROM THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

See Author Index in *Collected Reprints* 1950 for a complete list up to that year.

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